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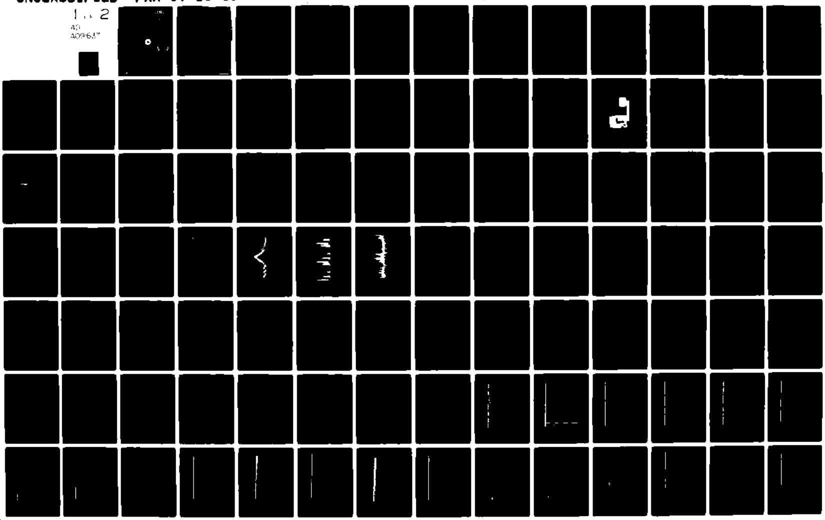

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FLIGHT TEST INVESTIGATION OF LORAN-C FOR EN ROUTE NAVIGATION IN THE GULF OF MEXICO

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DEPARTMENT OF TRANSPORTATION • UNITED STATES OF AMERICA •

FINAL REPORT

SEPTEMBER 1980

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16. Abstract

Flight tests of a long range navigation (LORAN-C) airborne navigator were conducted in the Gulf of Mexico oil exploration and production area. Two systems were installed in a CV-580 aircraft to examine simultaneously the performance from two different LORAN-C triads. Four separate test routes were flown over a period of 3 days. These routes covered the eastern, central, and western test areas, and an overland route from Houston, Texas, to Lafayette, Louisiana. An inertial navigation system (INS) was used as a position reference standard. The INS data were updated to correct for drift. Accuracy of the position reference from the corrected INS data was ±0.3 nautical miles (nmi). The flight test data collected indicated that both the Malone, Raymondville, Jupiter and the Malone, Raymondville, Grangeville triads provided en route LORAN-C navigation capability which met Federal Aviation Administration (FAA) Advisory Circular AC-90-45A accuracy requirements except when operating near the baseline extension of the Malone-Grangeville baseline when using the Malone, Raymondville, Grangeville triad.

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METRIC CONVERSION FACTORS

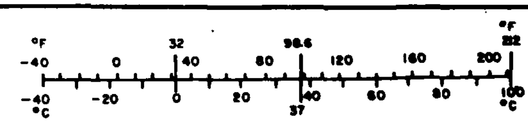
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

The purpose of this flight was to:

1. Examine en route accuracies of long range navigation (LORAN-C).

2. Examine differences in accuracies between two different triads covering the same geographic area.

3. Investigate the LORAN-C spectrum for potential sources of interference.

4. Document signal-to-noise ratios of LORAN-C stations in the coverage area.

The test area was the oil drilling and exploration area in the Gulf of Mexico.

BACKGROUND.

Within the continental United States, Alaska, and the offshore areas, helicopter operations are enjoying a growth rate in excess of 12 percent annually. With new advances in helicopter technology and avionics, an even larger percentage of these aircraft are capable of Instrument Flight Rules (IFR) all weather operations. Helicopter IFR operations require a navigation capability which, in many cases, cannot be met by conventional very high frequency omnidirectional radio range (VOR)/distance measuring equipment (DME) navigational aides in the National Airspace System. Two navigation systems which offer this capability are LORAN-C and Omega.

LORAN-C is a passive, pulsed low-frequency 100 kilohertz (kHz) hyperbolic radio navigation system that uses synchronized signals from three or more LORAN stations to obtain a position fix anywhere within the coverage area. Difference in time of arrival of pulses is a measure of difference in distance from the receiver to each of the stations. The locus of all points having the same observed difference in distance to a pair of stations is a hyperbola, called a line of position (LOP). The intersection of two or more LOP's defines position.

Coverage of an area depends upon transmitted power from each station and upon station geometry which also affects position determination accuracy. Variations in ground conductivity affect signal propagation; contributions from atmospheric and man-made noise degrade signal reception.

DISCUSSION

EQUIPMENT DESCRIPTION.

LORAN-C. The LORAN-C equipment used on this test was the Teledyne Systems TDL-711 LORAN Micro-Navigator distributed by Offshore Navigation, Incorporated. The system consists of three units: a control display unit (CDU), a receiver computer unit, and an antenna with integral coupler. The system is shown in figure 1. The control display unit provides the operator interface with the system and displays all navigation and self test functions. The receiver computer unit processes the LORAN-C signals and computes all navigation data using Great Circle computations. The receiver processor incorporates two adjustable notch filters which can be adjusted to remove two interfering frequencies. Both notch filters on each receiver were adjusted so as to be effectively removed from the circuit for these flight tests. The antenna is a whip antenna with an integral antenna coupler in the base. The antenna coupler provides impedance matching and bandpass amplification for the received LORAN-C signals. Two of these systems were installed in a Convair CV-580 aircraft.

INERTIAL NAVIGATION SYSTEM. A Litton LTN-51 Inertial Navigation System (INS) was used for primary course guidance and

position reference during the flight tests.

SPECTRUM ANALYZER. A Hewlett-Packard model 8581A Automatic Spectrum Analyzer was used for real time spectrum analysis of the LORAN-C frequency spectrum. The Automatic Spectrum Analyzer includes a model 8568A spectrum analyzer; a model 9825A desktop computer, a model 9866B printer, and a model 98216A plotter.

All of these equipments were rack mounted and installed in the CV-580 for these tests.

ROUTE STRUCTURE.

Four separate routes were flown in the test period from June 7-9, 1979. Three of the routes were constructed to cover a primary oil producing area in the Gulf of Mexico. These routes were designated the eastern, central, and western test routes. The test areas were defined as:

1. Eastern - between 89° and 91° longitude

2. Central - between 91° and 93° longitude

3. Western - between 93° and 95° longitude

These routes duplicated existing offshore helicopter routes whenever possible while still providing maximum coverage of the given area. These routes are depicted in figures 2 through 4, while the route waypoints are listed in tables 1 through 3. The fourth route was an overland route from Houston, Texas (Hobby Field), to Lafayette, Louisiana. The overland route is also depicted in figure 4. The distance between waypoints in nautical miles is depicted below each route segment on the figures. The routes were flown as follows:

1. East Gulf test area, June 7, 1979 - 1356 to 1755 hours CDT

2. West Gulf test area, June 8, 1979 - 0859 to 1245 hours CDT

3. Houston to Lafayette, June 8, 1979 - 1516 to 1719 hours CDT

4. Central Gulf test area, June 9, 1979 - 0915 to 1246 hours CDT

LORAN-C STATIONS USED.

A group of LORAN-C stations with a certain unique operating characteristic is called a chain. A LORAN-C chain consists of a master transmitting station designated M and two or more secondary transmitting stations designated W, X, Y, or Z. The unique operating characteristic which defines a chain is the time interval between the beginning of any two consecutive master pulse groups, known as the group repetition interval (GRI). Coverage within an area is provided when signals from the master and at least two secondaries can be received, and station geometry is such that accurate position fixes can be obtained.

Coverage of the operating area is provided by the Southeast United States (U.S.) Chain with a GRI of 79,800 microseconds (μs). The following stations make up the 7980 chain:

Malone, Fla.	Master
Grangeville, La.	W Secondary
Raymondville, Tex.	X Secondary
Jupiter, Fla.	Y Seconday

Carolina Beach, North Carolina, will be used as the Z secondary but was not yet rated for use with the 7980 chain when these flights were flown. The flight test area and the baselines between the master and the secondaries are shown on figure 5. Three stations within a chain are required for navigation. These three stations (a master and two

secondaries) form a triad. The selection of the two secondaries to form the triad must be done so that the intersection of the two lines of position in the general operating area is as close to 90° as possible. This geometry will provide the best accuracy of a position fix. When the lines of position cross at close to 90°, the area of uncertainity defined by the intersection of the lines is nearly square, as shown in figure 6.

When crossing angles decrease, the area of uncertainity becomes trapezoidol as shown in figures 7 and 8. In the case of figure 7, with the aircraft flight path as shown, one would expect larger along track errors than cross-track errors. The situation would be reversed if the aircraft flight path is changed by 90°, as shown in figure 8. The accuracy of a position fix will degrade as the crossing angle goes from 90° to 0°. Operation using LORAN-C should be avoided in areas with crossing angles less than approximately 30°. The TDL-711 systems used in these tests will track four LORAN-C stations but will only use three (the triad) for navigation. If one of the three selected for navigation purposes should fail, the system will go into a backup mode of navigation called master independence. In this mode of navigation, the two remaining stations of the prime triad are combined with the fourth station in track to form a new triad. Since the original prime triad is selected to give the most accurate position fix for the general operating area. The use of the fourth station to form a new triad may result in decreased accuracy. To examine this effect, the two LORAN-C receivers were configured to use two different triads for these flights. One receiver was configured to use Malone, Raymondville, and Jupiter while the other set was configured to use Malone, Grangeville, and Raymondville. With the sets configured in this manner, it was possible to simultaneously collect data on both the optimum and a backup triad configuration for that area. The Malone, Raymondville, Jupiter triad was expected to offer the best accuracy in the entire operational area.

BASELINE EXTENSION.

Another area of operation that will result in decreased accuracy is the baseline extension area. The baseline is a straight line drawn between the master and a secondary. Figure 5 illustrates the baselines between the master and all of the available secondaries for the 7980 chain. The baseline extension is the extension of a baseline indefinitely in both directions. Operations near or along baseline extensions should be avoided when using that master-secondary pair as part of the triad because of the resultant decrease in position accuracy.

The TDL-711 will continue to operate in this baseline extension area without warnings or indications of degraded position accuracy. Operators and certifying authorities must prohibit the use of LORAN-C in those geographic areas and triad configurations where the receiver will be operating in a baseline extension area.

AREA CALIBRATION.

Because of radio propagation anomalies, the position of a given point as computed and displayed by the LORAN-C may be different from the surveyed geographic position of that given point. The TDL-711 used in these tests has a feature which will allow the computation and application of a correction factor to bring the computed and displayed position in exact correspondence with the surveyed position. This procedure is called area calibration.

This procedure generally assumes that the propagation anomalies are the same for a given area, and that one calibration point can therefore

establish a correction factor for that entire area. The size of the area for which the calibration is valid is dependent on the uniformity of the propagation anomalies. It is possible that the establishment of a correction factor (area calibration) at a given point in an area, while improving the correspondence between the computed and displayed latitude/longitude (lat./long.) and the surveyed lat./long. at that point, could cause an error at another point which would be larger than if area calibration had not been applied. For this reason, the FAA and users must exercise care in approving and using area calibration and defining the area for which it is valid. For the flight tests conducted in the Gulf, area calibration was not used.

FLIGHT TEST PROCEDURES.

Prior to taxi for takeoff, the inertial navigation system was aligned and placed in the navigation mode. Both LORAN-C receivers were initialized and placed in the navigation mode. Both LORAN-C receivers were initialized and placed in the desired configuration. Once airborne, the data recording system was placed in operation. Spectrum analysis was done every 5 to 10 minutes throughout the flight.

All flights over water were conducted at 500 feet (ft) altitude. Overland portions of the flight were conducted at 1,000 ft. The aircraft was flown at 150 knots to simulate helicopter speeds as closely as possible.

DATA COLLECTION SYSTEM.

An FAA Technical Center designed and fabricated digital data collection system was utilized to collect system data. The data system is based on a Norden PDP-11/34M digital processor with 32K of memory, floating point processor and input/output (I/O) as necessary to support system peripherals. This is a militarized, hostile environment version of the Digital Equipment Corporation PDP-11/34 digital computer. A Miltope Corporation militarized dual floppy disc drive is used for data storage.

An aircraft systems coupler interfaces the various aircraft sensor signals to the computer's internal UNIBUS™ structure. The aircraft system coupler outputs 16 bit parallel words compatible with the PDP-11/34M. Table 4 lists the parameters that were recorded at a 1 hertz (Hz) rate for this flight test.

INERTIAL NAVIGATION SYSTEM UPDATE.

The LTN-51 Inertial Navigation System was used as the position standard for postflight determination of LORAN-C sensor errors. However, the INS is subject to drift rates which can approach 1 nautical mile/hour (nmi/hr). Obviously, if the INS was used without position updates for a 3.5 hour flight, the errors in the position measurement would be much greater than those expected for the LORAN-C. For this reason, the routes were established with a system of waypoints which were visually identifiable and which had known latitudes and longitudes. By visually identifying these waypoints, flying directly over them, and having the copilot use an event marker connected to the data acquisition system, the position of the aircraft at the given time could be accurately determined. This procedure was repeated at each waypoint on the route. Times between these waypoints varied from about 10 to 30 minutes.

INS error can be computed by comparing the measured INS position at the waypoint with the known position of the waypoint. By computing these errors at successive waypoints, INS drift could be approximated. Since relatively short periods of time elapsed between waypoints, INS drift was approximated as a linear function. Correction factors for both latitude and longitude could then be computed and applied to the

measured INS values at the 1 Hz rate. These correction factors were applied to the data during the post-flight data processing and reduction. Based on the observed values at the waypoints, the magnitude of the measured INS values at those points, and the frequency of update, it is believed that the INS position standard was accurate to within ±0.3 nmi. This must be considered when interpreting the quantitative data.

LORAN-C PERFORMANCE AND ADVISORY CIRCULAR (AC)-90-45A REQUIREMENTS.

Presently, approvals for the use of LORAN-C will be based on criteria contained in AC-90-45A, "Approval of Area Navigation Systems for Use in the U.S. National Airspace System." AC-90-45A was directed primarily at approval of VOR-DME random area navigation (RNAV) systems, but contains criteria for 2-D RNAV systems not using VOR/DME for continous navigation information. Table 5 contains the specific AC-90-45A limits for non-VOR/DME RNAV for the various airspaces. Quoting from AC-90-45A, "the total of the error contributions of the airborne equipment (including update, aircraft position, and computational errors), when combined with appropriate flight technical errors [listed in table 6] should not exceed the following [listed in table 5] with 95% confidence (2-sigma) over a period of time equal to the update cycle."

This means that the 2.5 nmi maximum crosstrack error for en route airspace is the root-sum-square (rss) of the 2.0 nmi flight technical error (FTE) and a 1.5 nmi airborne equipment crosstrack error allowance, or 2.5 = $\sqrt{(FTE)^2 + (Air\ Equip)^2} = \sqrt{(2)^2 + (1.5)^2}$

Since the data presented in this report is airborne equipment error only, and does not include FTE, the maximum allowable airborne system error from LORAN-C on a 95 percent probability basis, assuming the ±2.0 nmi value for FTE, would be ±1.5 nmi on a 2-sigma basis for the en route case. No FTE is used in determining along track accuracy. Therefore, maximum allowable airborne system error for the along track case in en route airspace is taken directly from table 5 and is 1.5 nmi.

TEST RESULTS

LORAN-C SYSTEM EN ROUTE ERRORS.

The errors presented in this section are LORAN-C system en route errors. These include errors that may exist in the airborne receiving and processing equipment, as well as errors that could occur in the transmission of the signal to the aircraft. The comparable error element analyzed in AC-90-45A would be the total of the error contributions of the airborne equipment (including update, aircraft position, and computational errors). The errors are computed by taking the difference in the latitudes and longitudes between the actual position as measured by the INS and the position as computed by the LORAN-C. The difference in the latitudes yield the northing error, while the difference in the longitudes yield the easting error. By rotating these errors to the aircraft desired track, along track and crosstrack errors result.

The resulting errors for each individual segment are presented in tables 7 through 44 inclusive. Each table presents the mean and standard deviation of the northing, easting, along track, and crosstrack errors for each of the two triads used on a particular segment of the route flown. Tables 7 through 20 inclusive, cover the eastern test area; tables 21 through 29 inclusive, cover the central test area; tables 30 through 41 inclusive, cover the western test area; and tables 42 through 44 cover the overland route.

Data samples are missing from some segments, and are not equal for the two different receivers on the same segment. This was caused by two factors. First, during flights, both FAA personnel and personnel from Offshore Navigation, Incorporated were closely monitoring performance and examing certain memory locations of the LORAN-C receiver processor units by entering a special diagnostic mode through the control display unit. However, unknown to the FAA or Offshore Navigation, Incorporated personnel, the serial digital data stream from the receiver processor unit freezes when the system is in the diagnostic mode. Since the serial digital data stream was supplying the data to the on-board recording system, this data had to be edited to remove those blocks of data recorded during the use of the LORAN-C system diagnostic mode.

Secondly, a problem in the software for the microprocessor interface for INS data resulted in some blocks of INS data being unusable. These data were also edited out before data analysis.

EASTERN TEST AREA.

A summary of the results obtained on the eastern test area flight is contained in table 45. This table contains the maximum mean error obtained in the eastern test area for northing, easting, crosstrack, and along track values for the two triads flown.

Also of note is the trend of the errors in the eastern test area. For the Malone, Raymondville, Jupiter data, the following trends were observed:

1. On all segments, the northing error was positive (+ = north).

2. On all but three segments, the easting error was negative (+ = east). On the three segments where the easting error is positive, the magnitude of the error is 0.1 nmi or less.

3. On all but two segments, the magnitude of the easting error was smaller than the magnitude of the northing error.

For the Malone, Grangeville, Raymondville data, the following trends were observed:

1. On all but one segment, the northing error was positive (+ = north). In the one case where the northing error was negative, the magnitude of the error was 0.02 nmi.

2. On all but four segments, the easting error was negative (+ = east). In those cases where the easting error was positive, the magnitude of the largest error was 0.09 nmi.

3. On all but three segments, the magnitude of the northing error was greater than that of the easting error.

Table 46 contains the maximum value obtained for each triad when taking the rss value of the northing and easting mean errors for each segment. These values are indicative of the maximum crosstrack or along track mean error that could be experienced in the eastern test area. Based on these numbers, plus the fact that typical one standard deviation for northing and easting errors were on the order of 0.07 nmi, it can be seen that either of the two triads flown in these tests will provide LORAN-C area navigation for en route purposes in the eastern test area, well within accuracies specified by AC-90-45A.

CENTRAL TEST AREA.

A summary of the results obtained on the central test area flight is contained in table 47. This table contains the maximum mean error obtained in the central test area for northing, easting, crosstrack, and along track values for the two triads flown.

Data trends found in the central test area were similar to those found in the eastern test area. For both triads flown, the following trends were observed:

1. On all segments, the northing error was positive (+ = north).

2. On all segments, the easting error was negative (+ = east).

3. On all but two segments, the magnitude of the northing error was greater than the magnitude of the easting error.

On two segments of the central test route, abnormally high standard deviations were in evidence. (See tables 26 and 27 for data on the Malone, Grangeville, Raymondville triad.) These high standard deviations were caused by erroneous LORAN-C position computations of short duration. These erroneous position computations would have caused an abrupt steering needle deflection and erroneous data on the CDU, but the duration was such that a pilot would never have followed the data. The data are valid, however, the cause is unknown.

Table 48 contains the maximum value obtained for each triad when taking the rss value of the northing and easting mean errors for each segment. These values are indicative of the maximum crosstrack or along track mean error could be experienced in the central test area.

Based on these numbers, plus the fact that typical one standard deviations for northing and easting errors were on the order of 0.07 nmi, it can be seen that either of the two triads flown in these tests will provide LORAN-C area navigation for en route purposes in the central test area, well within accuracies specified by AC-90-45A.

WESTERN TEST AREA.

LORAN-C operations within the western Gulf area present problems due to two factors:

1. The low signal strength from the Jupiter, Florida, LORAN-C station in this area.

2. The proximity of the baseline extension of the Malone-Grangeville baseline to the operating area.

Marginal signal strength from the Jupiter station in the western Gulf precludes the use of this station for 100 percent reliable navigation signals in this area. Data on this are presented in the section on Signal Strength Measurements.

The proximity of the baseline extension of the Malone-Grangeville baseline to the operating area affects LORAN-C accuracy in this area when using the Malone, Grangeville, Raymondville triad. Since LORAN-C accuracy in this area deteriorates as one travels north and west, the data from this triad was treated graphically rather than statistically.

Data from the Malone, Raymondville, Jupiter triad are summarized in table 49. This table contains the maximum mean error obtained in the central test area for northing, easting, crosstrack, and along track values. Some data trends for this test area are similar to those found in the other test areas:

1. On all but one segment, the northing error was positive (+ = north).

2. On all segments, the easting error was negative (+ = east).

The trend that was evident in the eastern and central test areas (northing errors larger than easting errors) was not evident in the western test area. The maximum value obtained for this triad, when taking the rss value of the northing and easting mean errors for each segment, was 0.60 nmi. This means that when using the Malone, Raymondville, Jupiter triad in the western test area, AC-90-45A en route accuracies can easily be met. Low signal strength of the Jupiter station in this area precludes the use of this triad for reliable navigation in this area.

Data collected on the Malone, Grangeville, Raymondville triad in the western test area were subjected to a statistical analysis, but after examining the results of the statistical analysis and the graphical error plots, it was decided that the data would be best treated by graphical means rather than statistical methods. The reason for this decision was that in the western test area, as one proceeds in a westerly and/or northerly direction, error values change quite rapidly due to the effects of the baseline extension of the Malone-Grangeville baseline. With rapidly changing error values, means and standard deviations can present a misleading picture of what is actually happening.

Figure 9 is an error plot of along track, crosstrack, northing, and easting errors for the Intracoastal City to Cameron segment in the western test area. On this segment, as the aircraft tracks in a westerly direction, errors increase. Figure 10 is an error plot of the Cameron to East Cameron Block No. 64, Platform A segment. Error values decrease as the aircraft travels in a southeasterly direction. Figure 11, by comparison, shows the same error values for the same segment but with the Malone, Raymondville, Jupiter triad being used for navigation. Error values are constant along the route. Figure 12 shows a continuing trend toward decreasing errors as the aircraft continues in a southeasterly direction.

Figures 13 and 14 are the error plots for the West Cameron Block No. 587, Platform A to Sabine Pass segment. On this segment, the aircraft is traveling in a predominatly northerly direction and errors, particularly northing and along track errors, increase as the aircraft travels in this northerly direction.

Decreases in error values are evident in the Sabine Pass To West Cameron No. 45-4 segment (figure 15). Here the aircraft is traveling in a southeasterly direction.

Figure 16 contains the error plots for the West Cameron Block No. 45-4 to Cameron segment. The aircraft is traveling in a northeasterly direction, and error values remain fairly constant. Increases in error values are seen in figure 17 (aircraft traveling in a westerly direction), whole decreases in error values are seen in figure 18 (aircraft traveling in southwesterly direction). As the aircraft continues in a southwesterly direction, a further slight decrease in error values is evident (figure 19).

As can be seen from the graphic data, when using the Malone, Grangeville, Raymondville triad, en route navigation accuracy is not always in compliance with AC-90-45A. With the data available, it is not possible to accurately define the boundary between areas of compliance and noncompliance. Further tests will be necessary to accurately define this contour.

HOUSTON TO LAFAYETTE OVERLAND ROUTE.

Data for the Malone, Raymondville, Jupiter triad for the overland route are presented in tables 42 through 44 inclusive. As can be seen, compliance with AC-90-45A en route accuracy

requirements is maintained over the entire route when using the Malone, Raymondville, Jupiter triad. Low signal strength of the Jupiter station in the western part of the route precludes its use for reliable navigation.

Operations along this route using the Malone, Grangeville, Raymondville triad exhibited the same baseline extension effects that were seen in the western test area. Errors as large as 6 nmi were evident in the Houston area, with errors decreasing as the aircraft traveled in an easterly direction.

DATA COMPOSITE.

The data from all flights were then aggregated in blocks of 1/2 degree latitude by 1/2 degree longitude. The numbers in each block of figure 20 represent the northing and easting errors of the Malone, Raymondville, Jupiter and the Malone, Grangeville, Raymondville triads, respectively.

As can be seen, the Malone, Raymondville, Jupiter triad provides accuracy in compliance with AC-90-45A throughout the test area when the signal strength is adequate.

The effects of the baseline extension of the Malone-Grangeville baseline is clearly illustrated by the error figures for the Malone, Grangeville, Raymondville triad. The large error figures should be interpreted with caution because of the fact that the errors in the baseline extension area change rapidly with changes in position. The mean errors in this area will have high standard deviations. The effects of the Malone-Grangeville baseline are evident as one proceeds north and west.

LORAN-C SIGNAL STRENGTH MEASUREMENTS.

The TDL-711 LORAN-C receiver measures the signal-to-noise ratio (SNR) of the four LORAN-C stations that it is set up to receive. This information is part of the data that were recorded during the Gulf Coast LORAN-C test flights.

A typical plot is shown in figure 21. The horizontal time axis is identical for all four plots. The vertical axes are SNR's for Jupiter (y), Raymondville (x), Grangeville (w), and Malone (master), respectively, top to bottom. The LORAN receiver used does not indicate SNR's greater than +5 decibels (dB) and the data limits at that point. The dots or bars immediately above the individual data plots indicate an out-of-track condition for that signal; for example, all four stations were out-of-track for about 1 minute at approximately 0901 while the receiver was being reinitialized. Additionally, the Jupiter station was never in-track until slightly past 1005 hours.

All of the SNR data is plotted and presented in appendix A in figures A-1 through A-26. The data are alternately presented for receiver 1, then receiver 2 for the same time period.

An analysis of these plots shows the following results: The signals from Malone, Grangeville, and Raymondville show at least +5 dB SNR throughout the entire area covered by the test flights. The TDL-711 will not compute a signal-to-noise ratio if the SNR is better than +5 dB.

For the eastern test area flight, Jupiter shows an SNR of about +3 dB for both receivers. For the flight in the central test area, an SNR of about +3 dB is seen for Jupiter on receiver No. 2 throughout the flight. Receiver No. 1 presents a different result. The Jupiter station was not acquired during the early portions of the flight (figure A-17). At approximately 0918, Jupiter was acquired briefly, for about 5 minutes, with an SNR of about -5 dB. The signal was again lost (figures A-19 and A-21) until approximately 1135 when

it was reacquired with an SNR of about -3 dB. Since the LORAN-C antennas were in the same approximate location, it appears as though there was a difference in the sensitivity between the two receivers. For the Houston to Lafayette flight, again receiver No. 1 would not acquire the Jupiter station. Receiver No. 2 acquired Jupiter with an SNR of about 0 dB, increasing to a maximum of +3 dB as the flight progressed from west to east. For the western test area gulf flight, receiver No. 2 acquired and tracked Jupiter with SNR's between +2 to +4 dB. During the early part of the flight, receiver No. 1 could not acquire Jupiter. At about 1006, Jupiter was acquired and tracked at an SNR of -2 dB. Signal strength of the Jupiter station, as measured by receiver No. 1, decreased as the flight proceeded is a westerly direction, decreasing to about -8 dB in the Houston area. It has been the experience of the distributor of this model of LORAN-C that, during their test flights in this area, Jupiter provides a usable signal on an intermittent basis. The problem is most severe in the western test area and becomes less severe in the eastern test area.

SPECTRUM ANALYSIS RESULTS.

Figure 22 is typical of the type of plot obtained during spectrum search operations during the data flights. This data were taken on June 8, 1979, at 1118 local time during the western test area flight; approximate position was N29° 48.0, W93° 51.0. The LORAN-C spectrum is shown from about 90 to 110 kHz with no strong interfering signals evident in that band.

Figure 23 is a single sweep of 200 milliseconds (ms) at 100 KHz. This sample was taken on the central test area route at 1100 hours local time at a position of approximately 29°28.0' N and 91°52.3' W. This figure clearly shows the individual pulses in each pulse group and the relationship of each pulse group to the master. The master pulse group is identified in this figure. It has a total of nine pulses in its pulse group with a space between the eighth and ninth pulse. The other pulse groups of the secondaries each contain eight pulses. The GRI of 79,800 μs measured between the beginning of any two consecutive master pulse groups is the characteristic GRI for the Southeast U.S. chain. The relative amplitudes of each of the pulse groups can be seen, with Jupiter, Flordia, at about -50 decibels above 1 milliwatt (dBm), well below the others.

Figure 24 is another single sweep of 200 ms at 100 kHz. This was done with the aircraft on the ground at Hobby Airport, Houston, Texas. As can be seen, there is a very high level of spike interference overriding the LORAN-C pulses. The Malone, Florida, and Jupter, Florida, pulse groups are almost obscured by this interference. This interference prevented the LORAN-C navigator from being initialized to the Malone, Raymondville, Jupiter triad while at this location.

There is an industrial park in close proximity to Hobby Field which could be the source of this type of interference. The distributor of the TDL-711 LORAN-C receiver, Offshore Navigation, Incorporated, has reported similar experiences in this area, with the interference occuring during weekdays only, in a time period from 0800-1700 local time. The time frame of the interference would indicate a day-to-day industrial operation. The notch filters on the LORAN-C receiver processor unit are not effective in removing this type of interference.

During the course of the data flights, the spectrum was closely monitored for any traces of interference that might emanate from the multitude of platforms supporting the oil drilling and production in the Gulf of Mexico. No traces of any such interference was found in the offshore area.

SUMMARY OF RESULTS

1. En route mean error data were aggregated into blocks of 1/2 degree latitude by 1/2 degree longitude covering the test area. The range of values seen in these blocks over the test area were as follows:

A range from -0.3 to 0.7 nmi for mean northing error (+ = north) when using the Malone, Raymondville, Jupiter triad; a range from -0.5 to 0.3 nmi for mean easting error (+ = east) when using the Malone, Raymondville, Jupiter triad.

Data for the Malone, Raymondville, Grangeville triad are complicated by the fact that part of the test area is located in the baseline extension area of the Malone-Grangeville baseline, and very large errors occur when operating in a baseline extension area. As one travels in a northerly and westerly direction, particularly in the western test area, baseline error effects become very pronounced.

The following data were observed outside the baseline extension area: A range from 0.1 to 0.7 nmi for mean northing error (+ = north) when using the Malone, Raymondville, Grangeville triad. A range from -0.3 to 0.1 nmi for mean easting error (+ = east) when using the Malone, Raymondville, Grangeville triad.

Northing errors over 6 nmi and easting errors over -4 nmi were observed in the Galveston-Houston, Texas, area when using the Malone, Raymondville, Grangeville triad and operating in the Malone-Grangeville baseline extension area.

2. Differences between the mean northing and easting errors of the two triads observed were typically 0.2 nmi or less as long as operation was not being conducted in the area of the Malone-Grangeville baseline extension.

3. No interference which would cause difficulties with the LORAN-C system was observed during the test flights in the offshore portions of the route. Severe interference was detected on and around Hobby Field, Houston, Texas. The interference was severe enough to prevent the LORAN-C navigator from being initialized to weaker stations while on the ground at Hobby Field.

4. Signal-to-noise ratios measured by the TDL-711 LORAN-C system for Malone, Raymondville, and Grangeville showed +5 dB, the maximum the system is capable of computing and outputting. Signal-to-noise ratios measured on Jupiter varied from a maximum of +3 dB in the eastern test area to an intermittently unusable signal in the western test area.

CONCLUSIONS

1. In the test area, the two long range navigation (LORAN-C) triads (Malone, Raymondville, Jupiter and Malone, Raymondville, Grangeville) of the Southeast United States (U.S.) Chain provide en route navigation capability which meets Advisory Circular-90-45A en route accuracy requirements, except when using the Malone, Raymondville, Grangeville triad and operating in the baseline extension area of the Malone-Grangeville baseline.

2. Differerces in accuracies between the two triads used in the test area are small enough (typically 0.2 nautical miles (nmi) or less except when using the Malone, Raymondville, Grangeville triad and operating in the baseline extension area of the Malone-Grangeville baseline) to allow the use of either of the two triads as a backup to the prime (other) triad for en route navigation purposes with only minor discontinuities occuring at triad changeover.

3. Interference (presumably man-made) was detected on and around Hobby Field, Houston, Texas, which prevented the initialization and proper operation of the LORAN-C navigator.

4. Interference of the type (broad spectrum) detected on Hobby Field cannot be removed by the notch filters in the navigator.

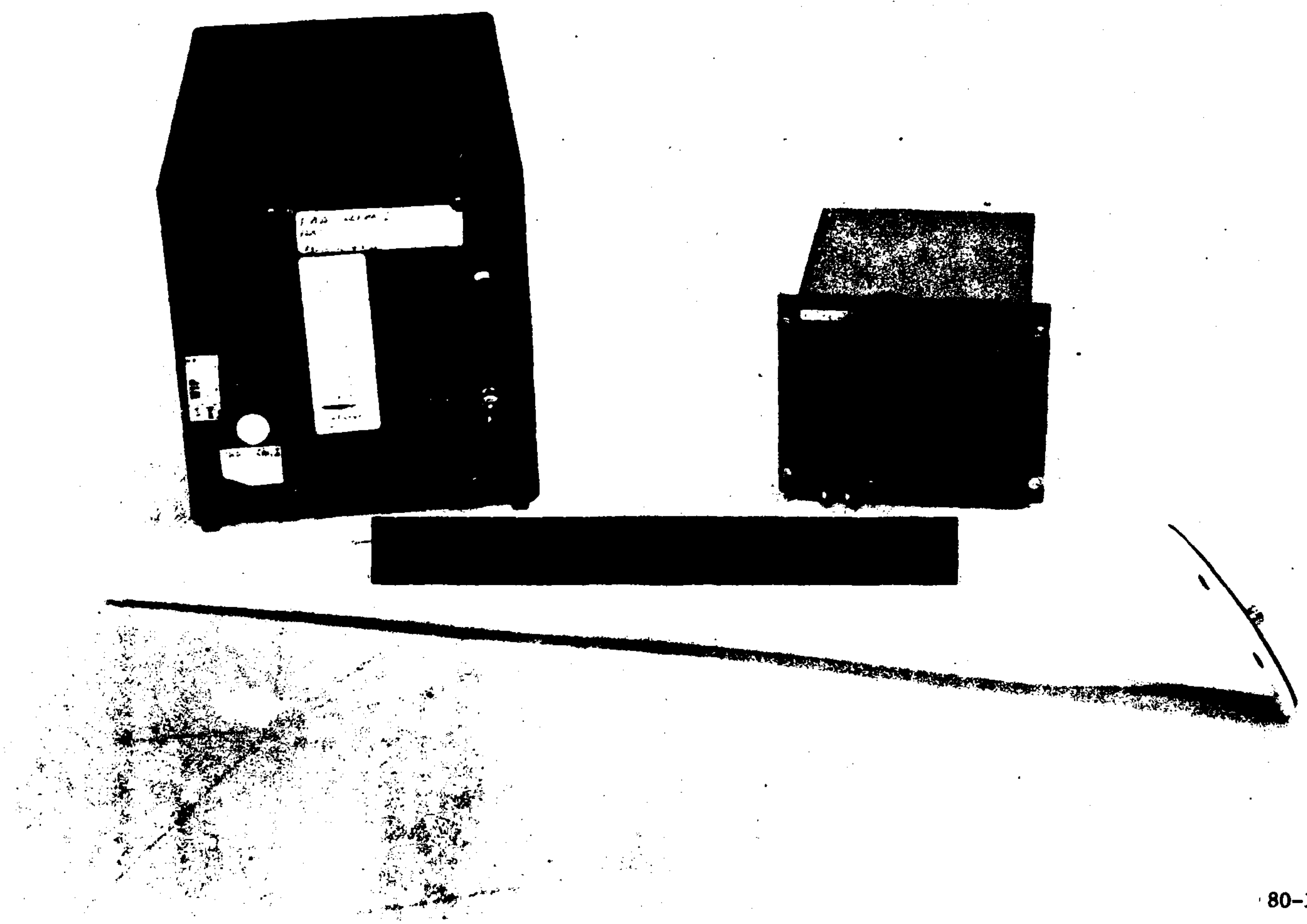
5. The Malone, Grangeville, and Raymondville LORAN-C stations provide high signal-to-noise ratios throughout the test area. The Jupiter, Florida, LORAN-C Station cannot be relied on to provide a usable signal (when using the TDL-711 and TDL-418 antenna) 100 percent of the time when operating in the western test area and parts of the central test area. However, adequate signal-to-noise ratios were measured from the Jupiter station in the eastern test area.

RECOMMENDATIONS

Additional tests should be conducted to:

1. Establish a contour which represents Advisory Circular-90-45A compliance in the western test area when using the Malone, Grangeville, Raymondville triad.

2. Examine area calibration as a method of improving accuracy in the western test area.



80-18-1

FIGURE 1. TDL-711 LORAN-C SYSTEM

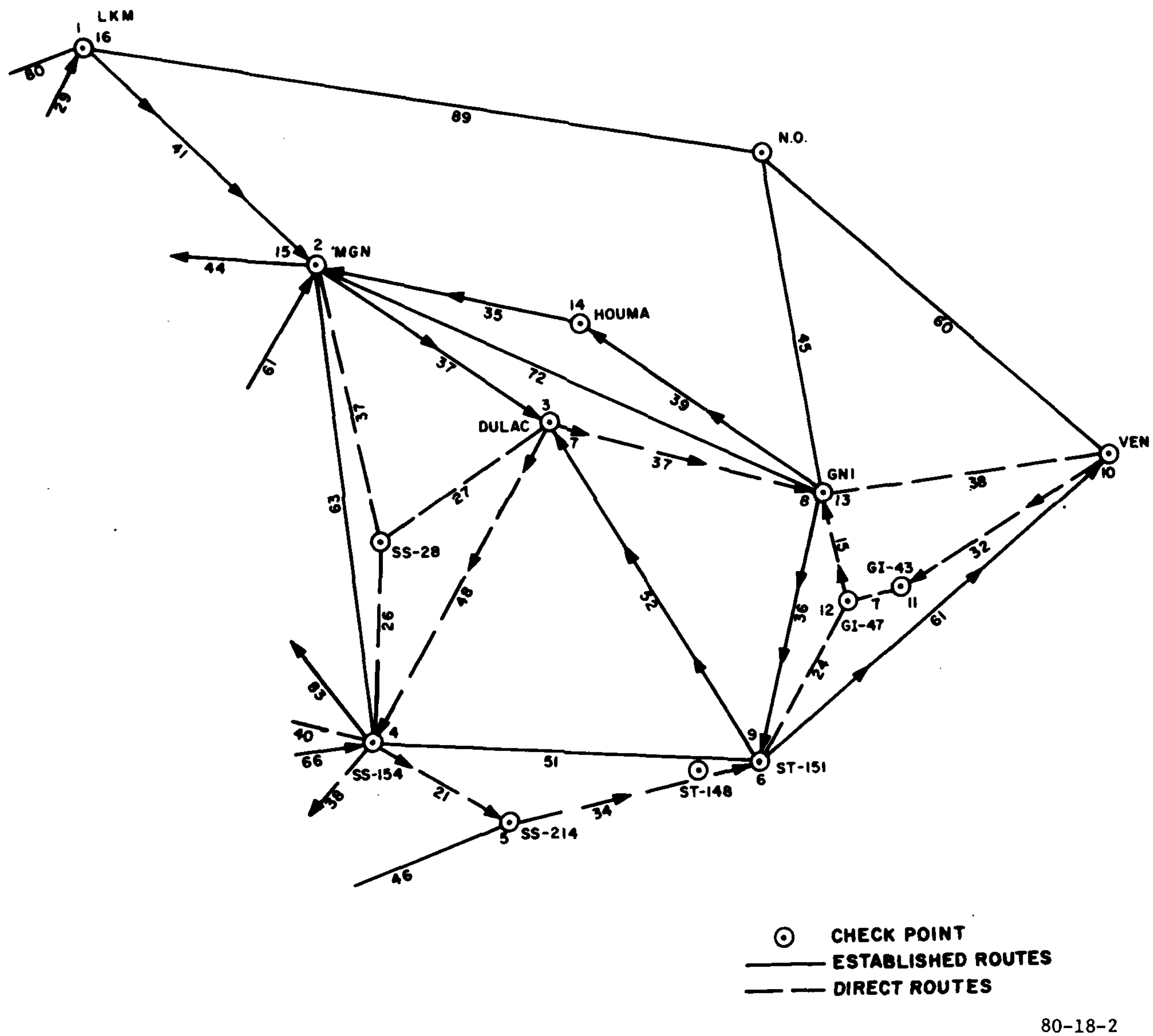


FIGURE 2. EASTERN TEST AREA ROUTE

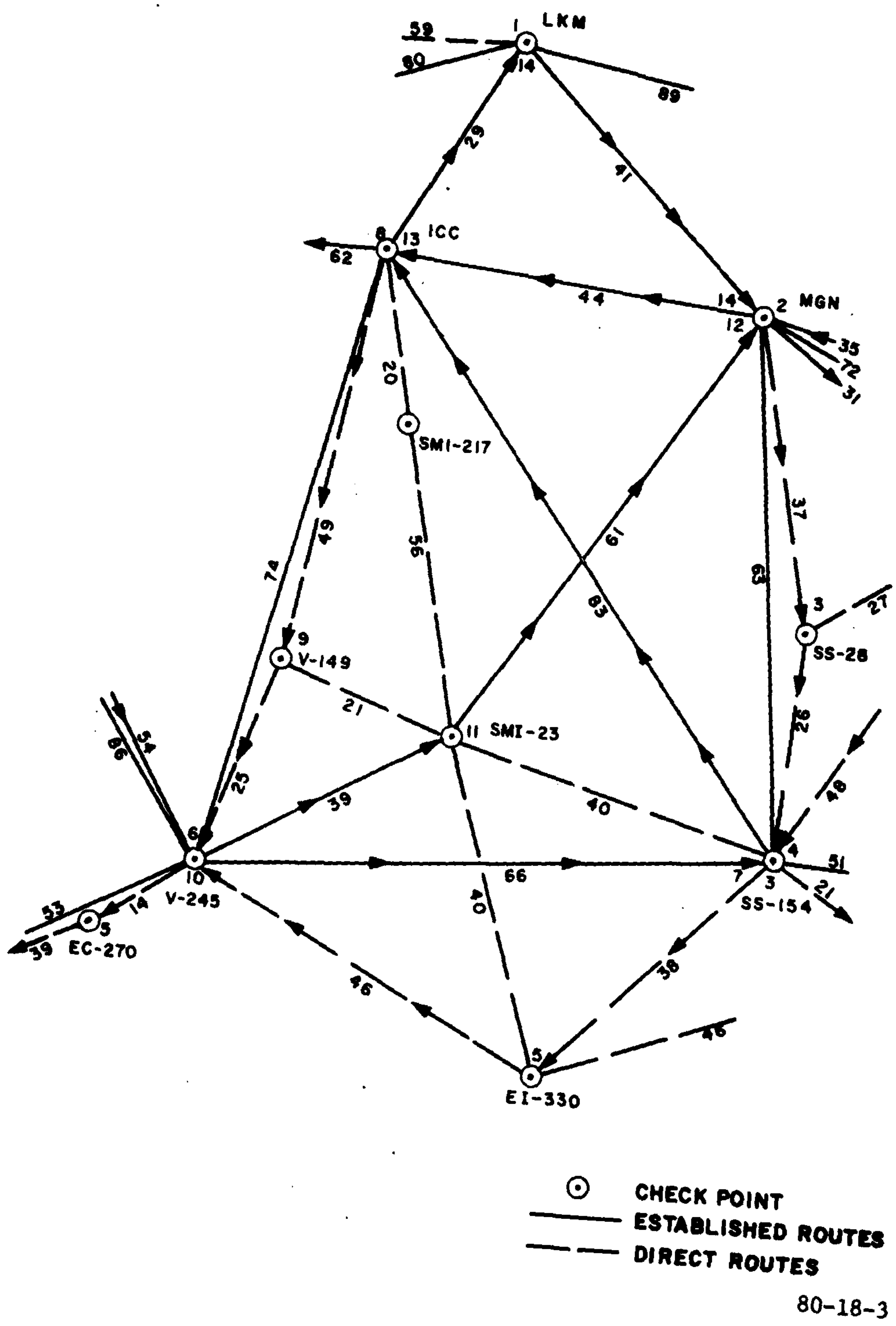
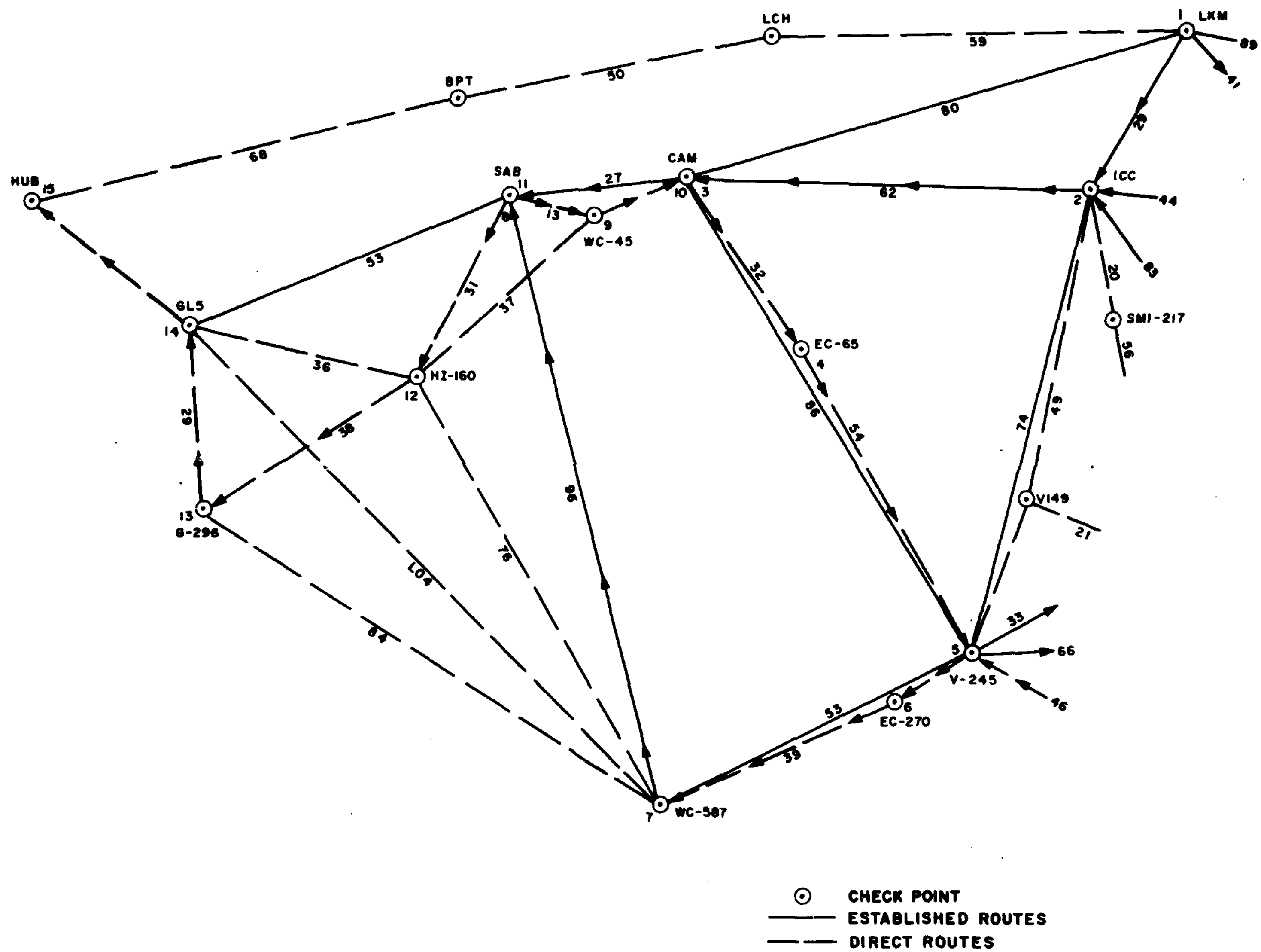


FIGURE 3. CENTRAL TEST AREA ROUTE



80-18-4

FIGURE 4. WESTERN TEST AREA ROUTE AND OVERLAND ROUTE

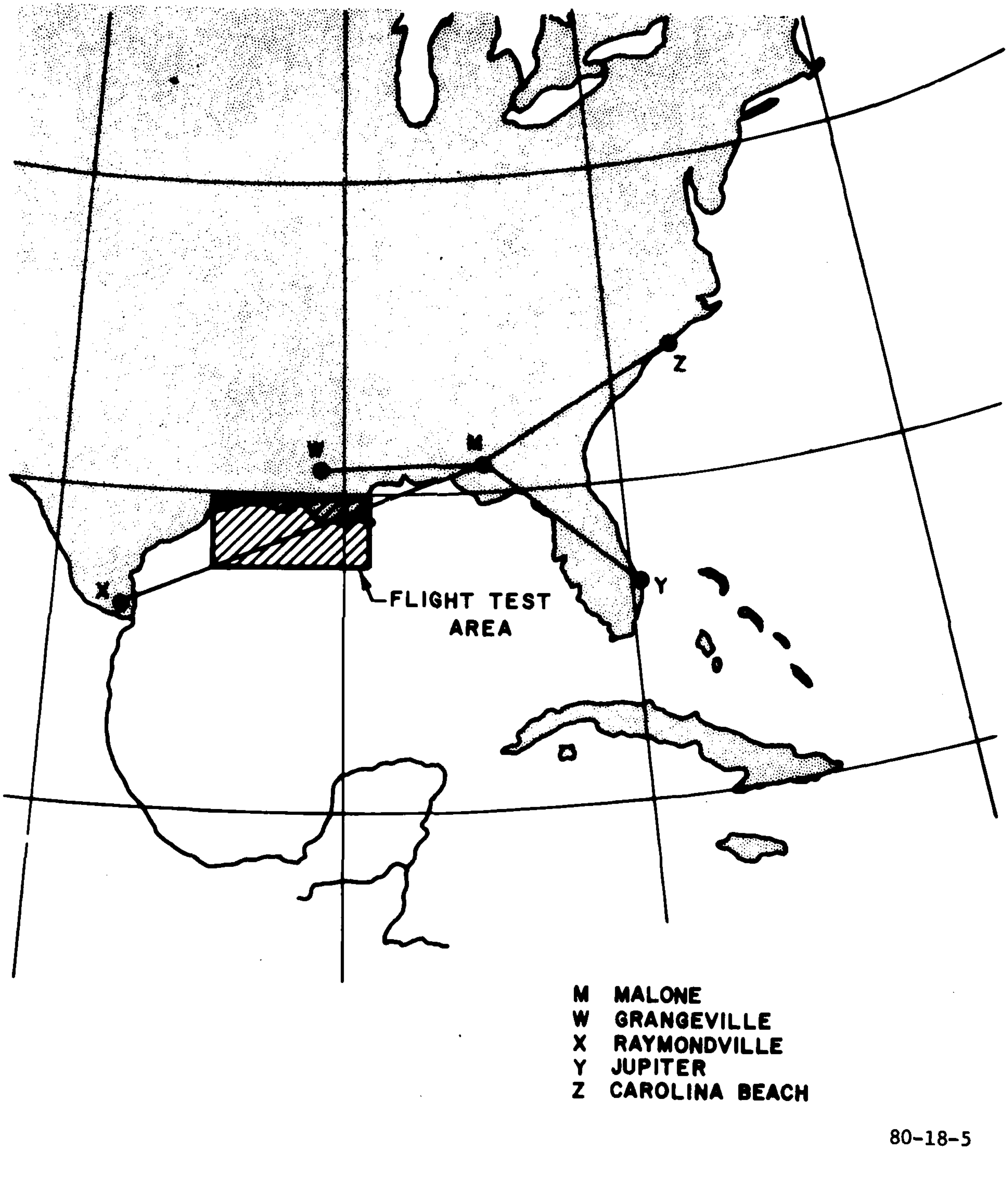


FIGURE 5. U.S. SOUTHEAST LORAN-C CHAIN GEOMETRY

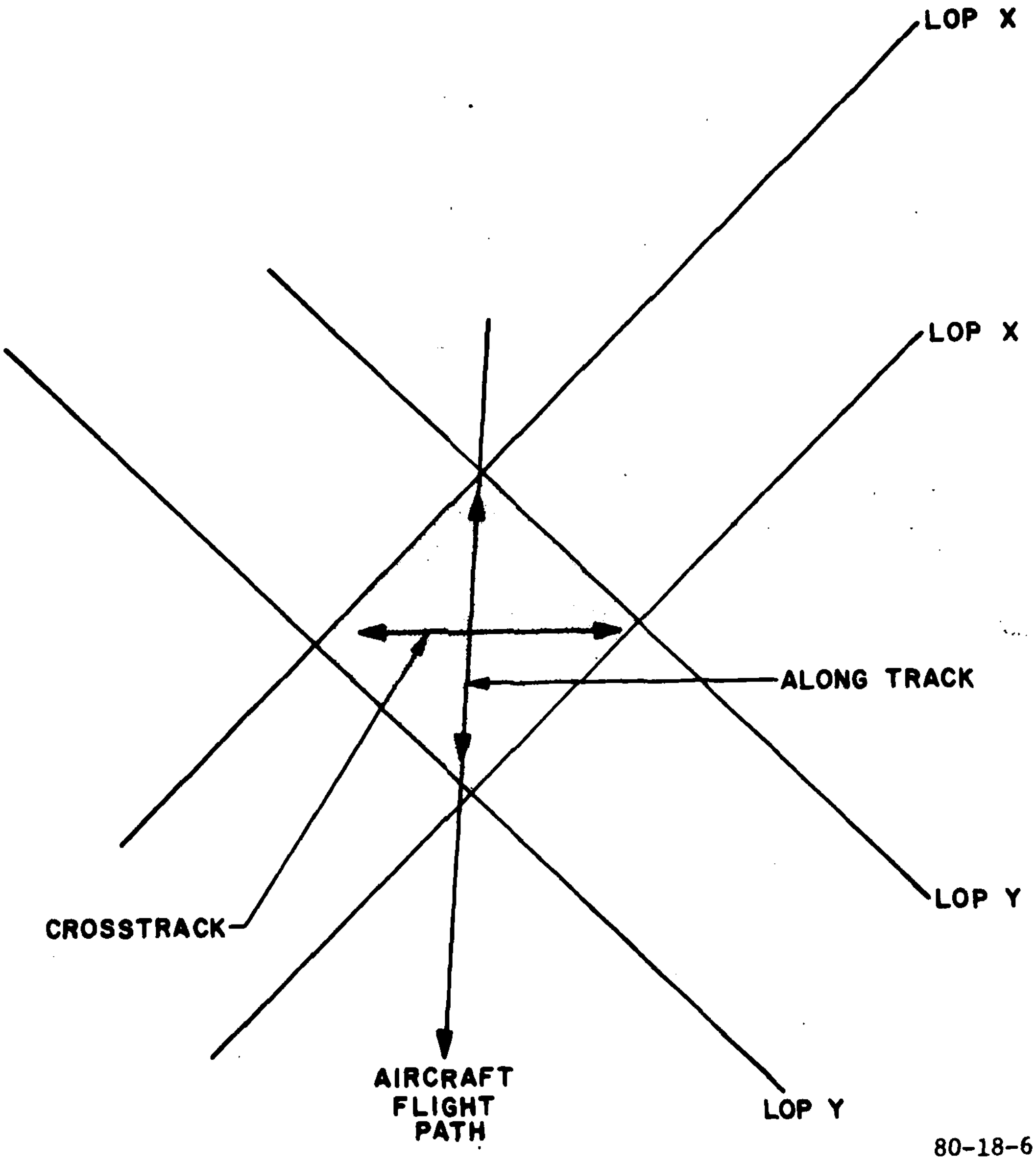


FIGURE 6. LORAN-C CROSSTRACK AND ALONG TRACK GEOMETRY CONSIDERATIONS—ALONG TRACK AND CROSSTRACK ERRORS EQUAL

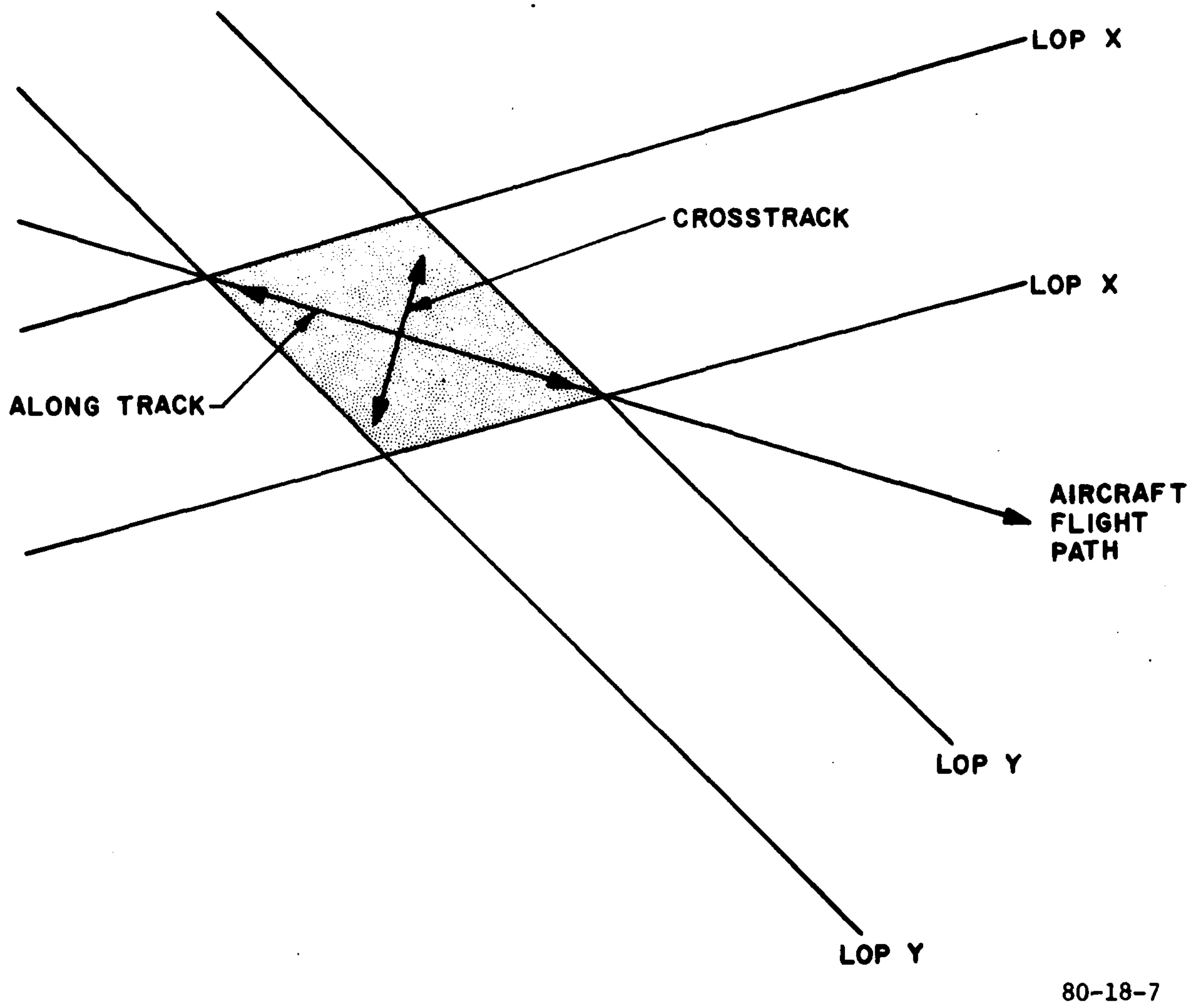


FIGURE 7. LORAN-C CROSSTRACK AND ALONG TRACK GEOMETRY CONSIDERATIONS—ALONG TRACK ERROR PREDOMINANT

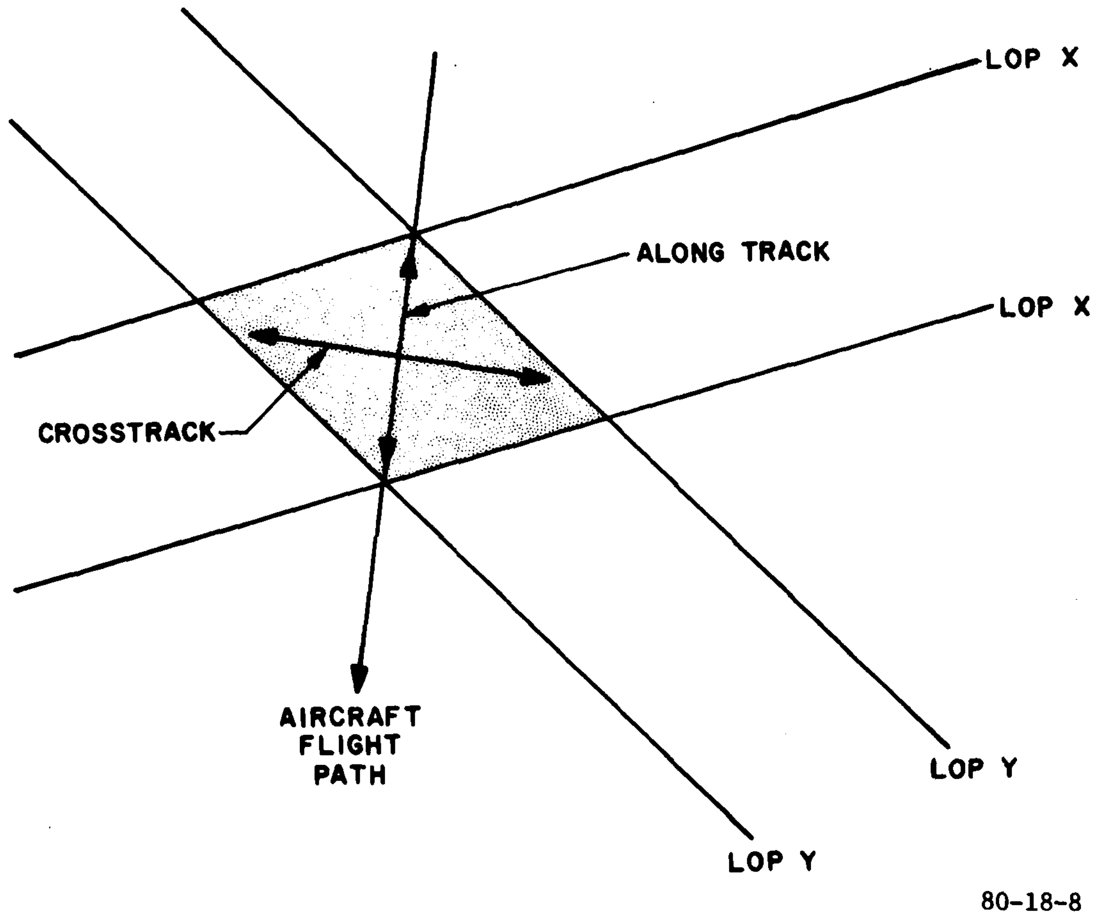


FIGURE 8. LORAN-C CROSSTRACK AND ALONG TRACK GEOMETRY CONSIDERATIONS—CROSSTRACK ERROR PREDOMINANT

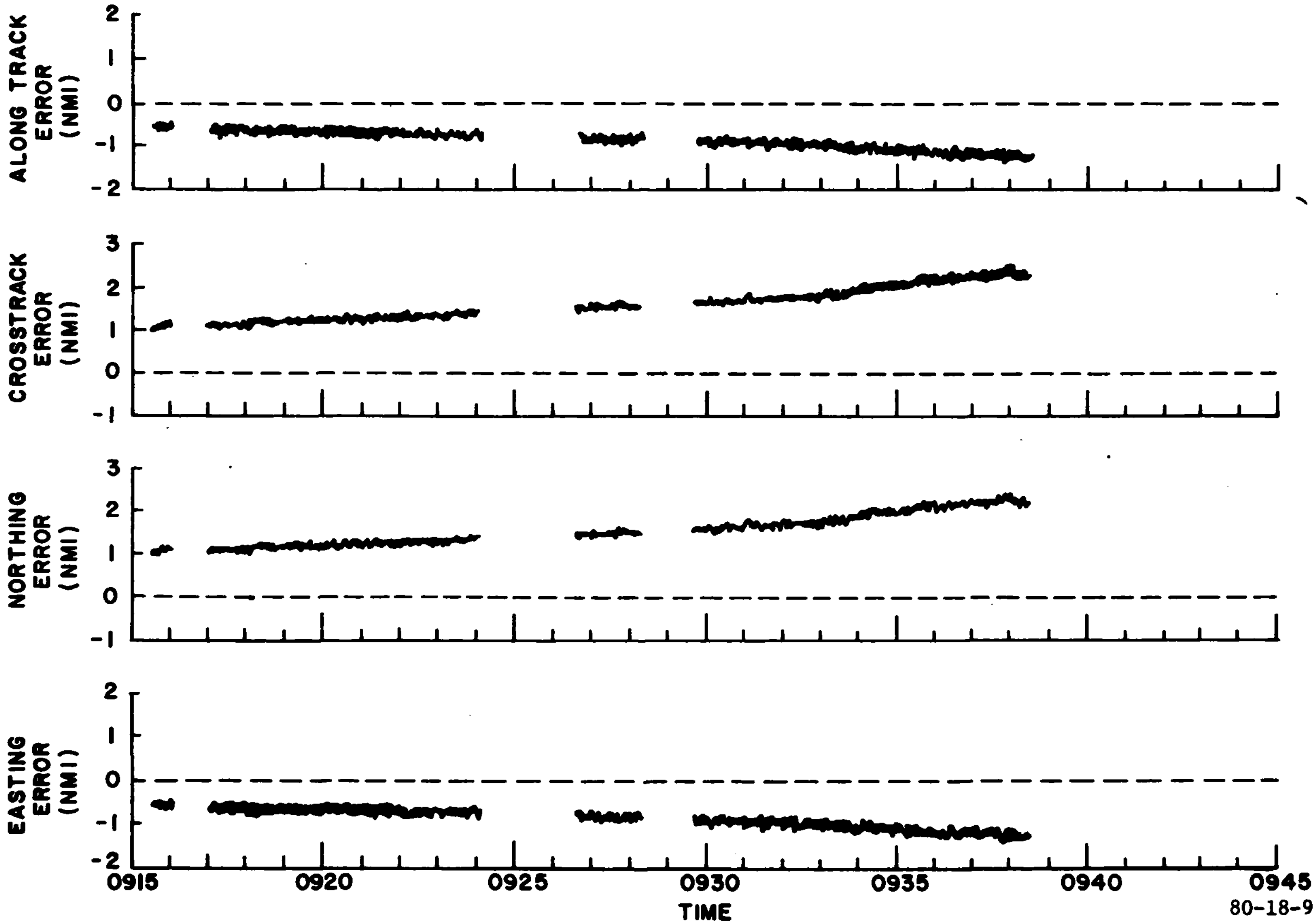


FIGURE 9. ERROR PLOTS FOR WESTERN TEST AREA, INTRACOASTAL CITY (PHI HELIPORT) TO CAMERON (PHI HELIPORT), MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

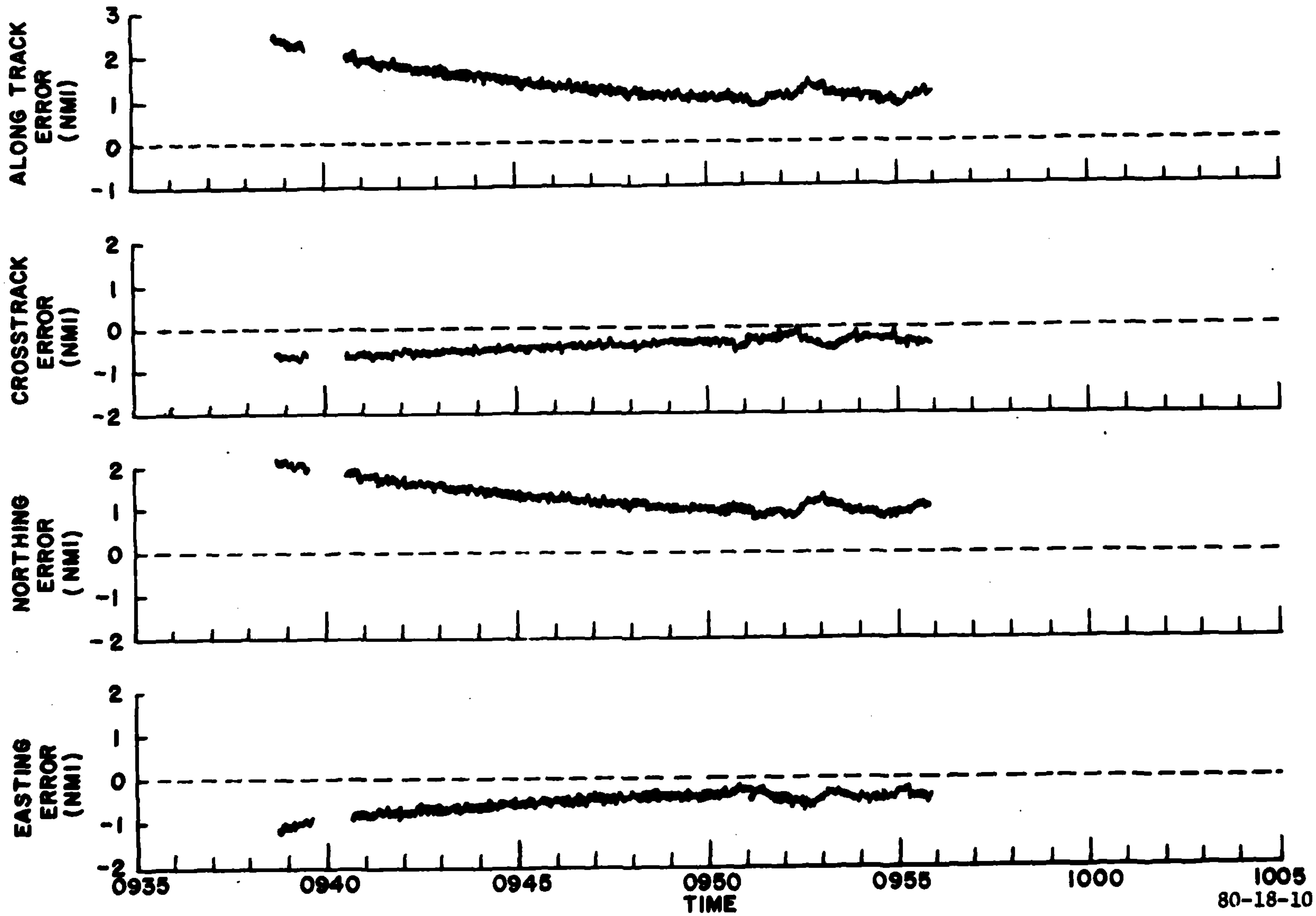


FIGURE 10. ERROR PLOTS FOR WESTERN TEST AREA, CAMERON (PHI HELIPORT) TO EAST CAMERON BLOCK NO. 64, PLATFORM A, MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

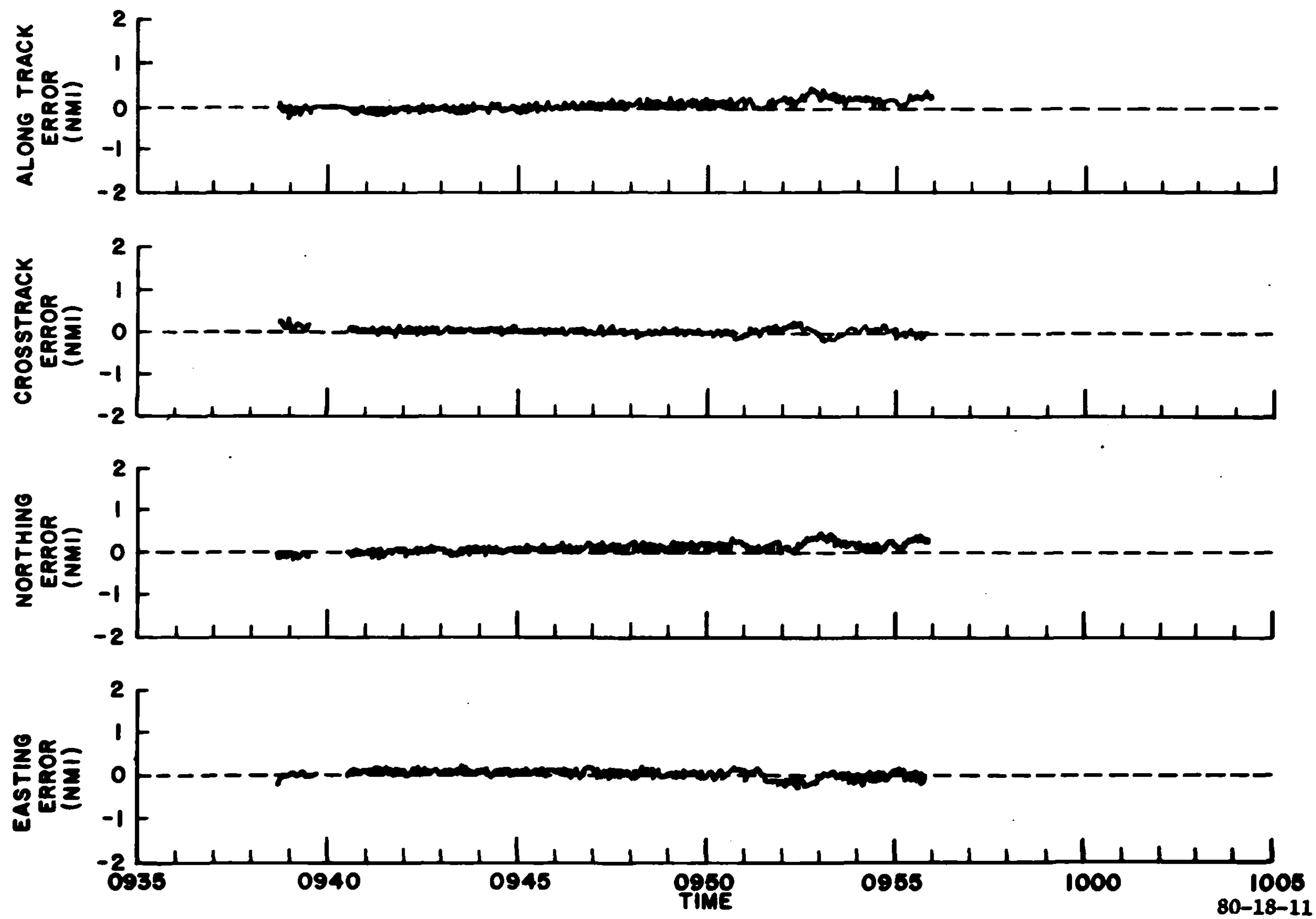


FIGURE 11. ERROR PLOTS FOR WESTERN TEST AREA, CAMERON (PHI HELIPORT) TO EAST CAMERON BLOCK NO. 64, PLATFORM A, MALONE, RAYMONDVILLE, JUPITER TRIAD

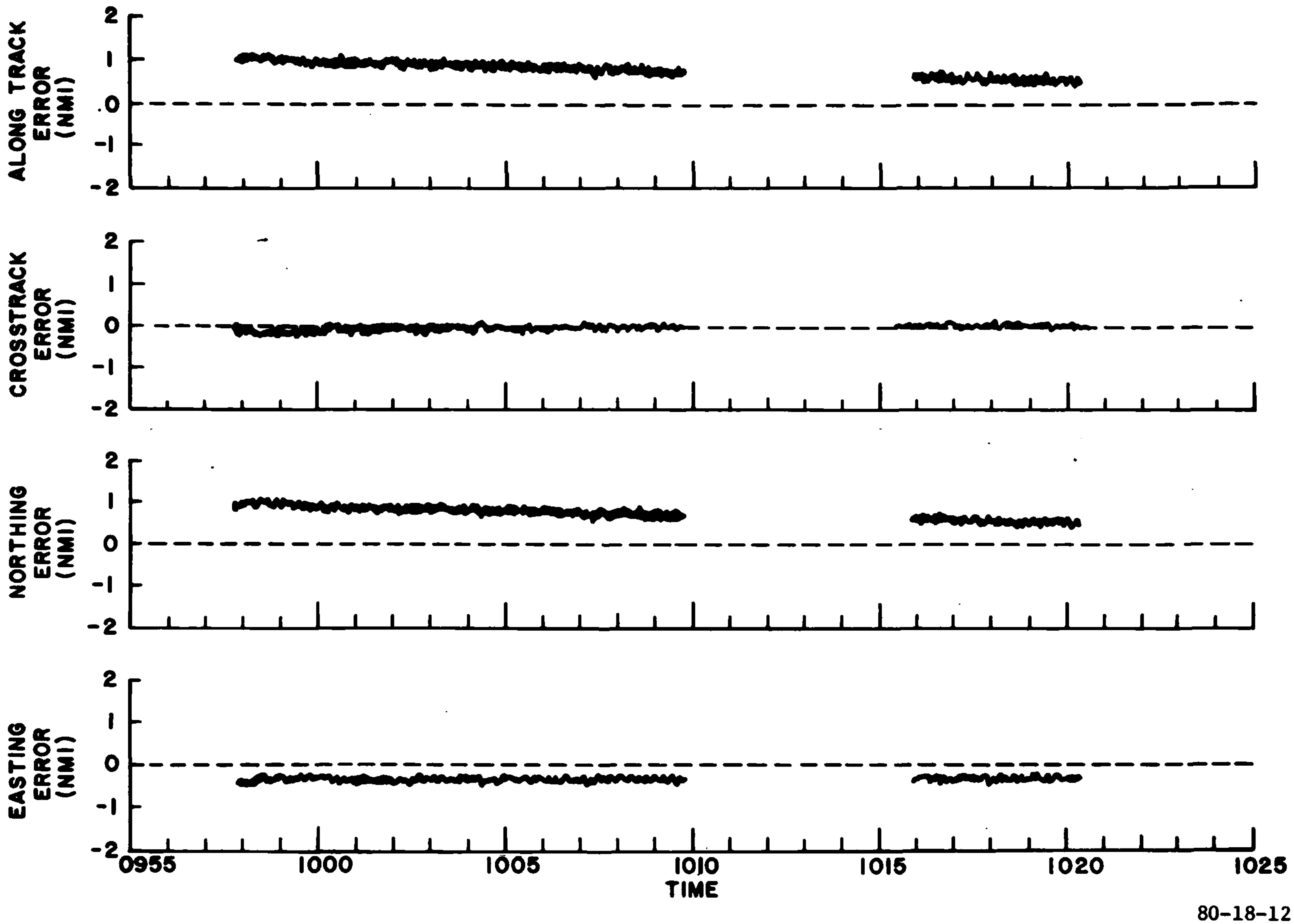


FIGURE 12. ERROR PLOTS FOR WESTERN TEST AREA, EAST CAMERON BLOCK NO. 64, PLATFORM A, TO VERMILION BLOCK NO. 245, PLATFORM A, MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

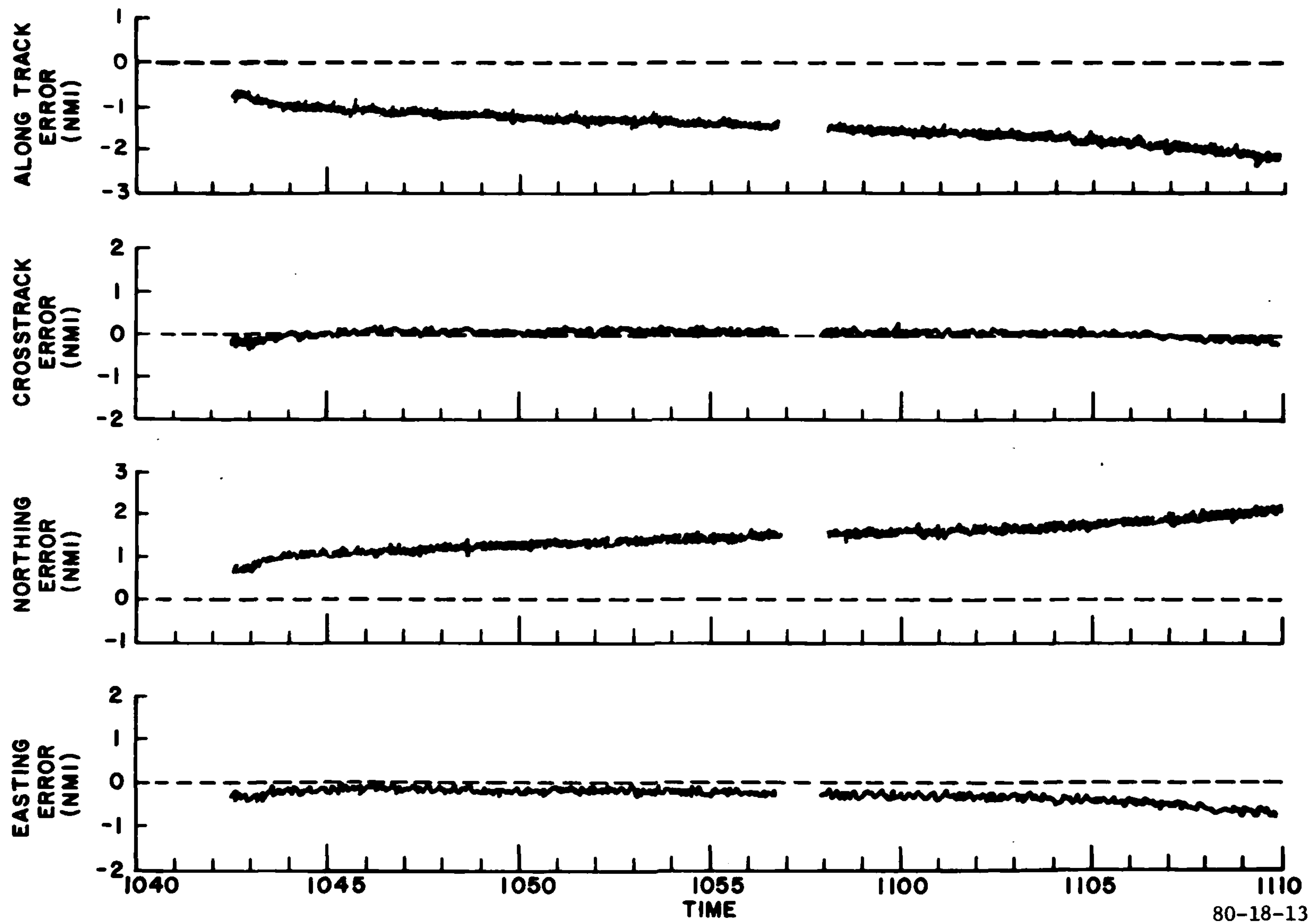


FIGURE 13. ERROR PLOTS FOR WESTERN TEST AREA, WEST CAMERON BLOCK NO. 587, PLATFORM A, TO SABINE PASS (PHI HELIPORT), MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

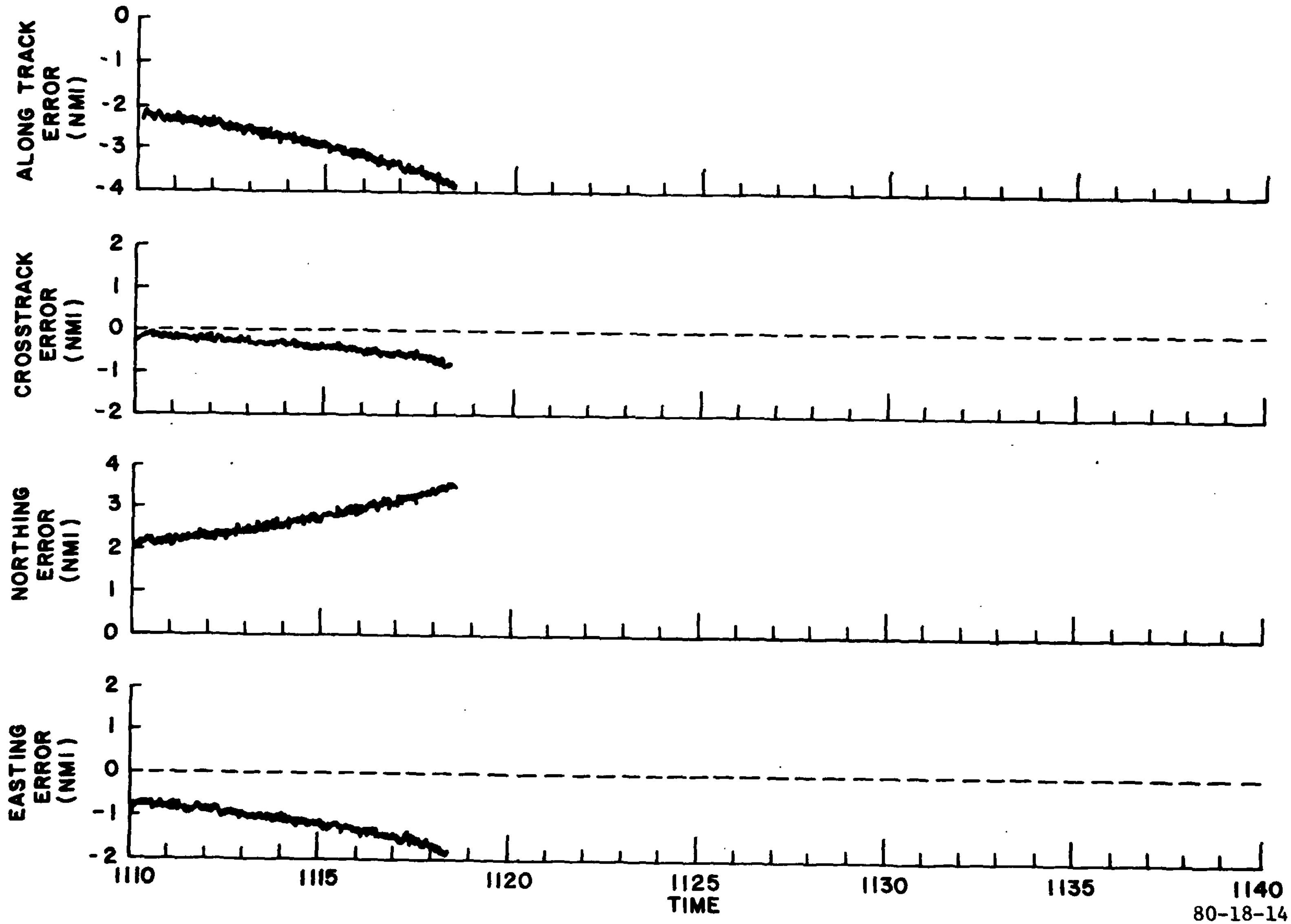


FIGURE 14. CONTINUATION OF ERROR PLOTS FOR WESTERN TEST AREA, WEST CAMERON BLOCK NO. 587, PLATFORM A, TO SABINE PASS (PHI HELIPORT), MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

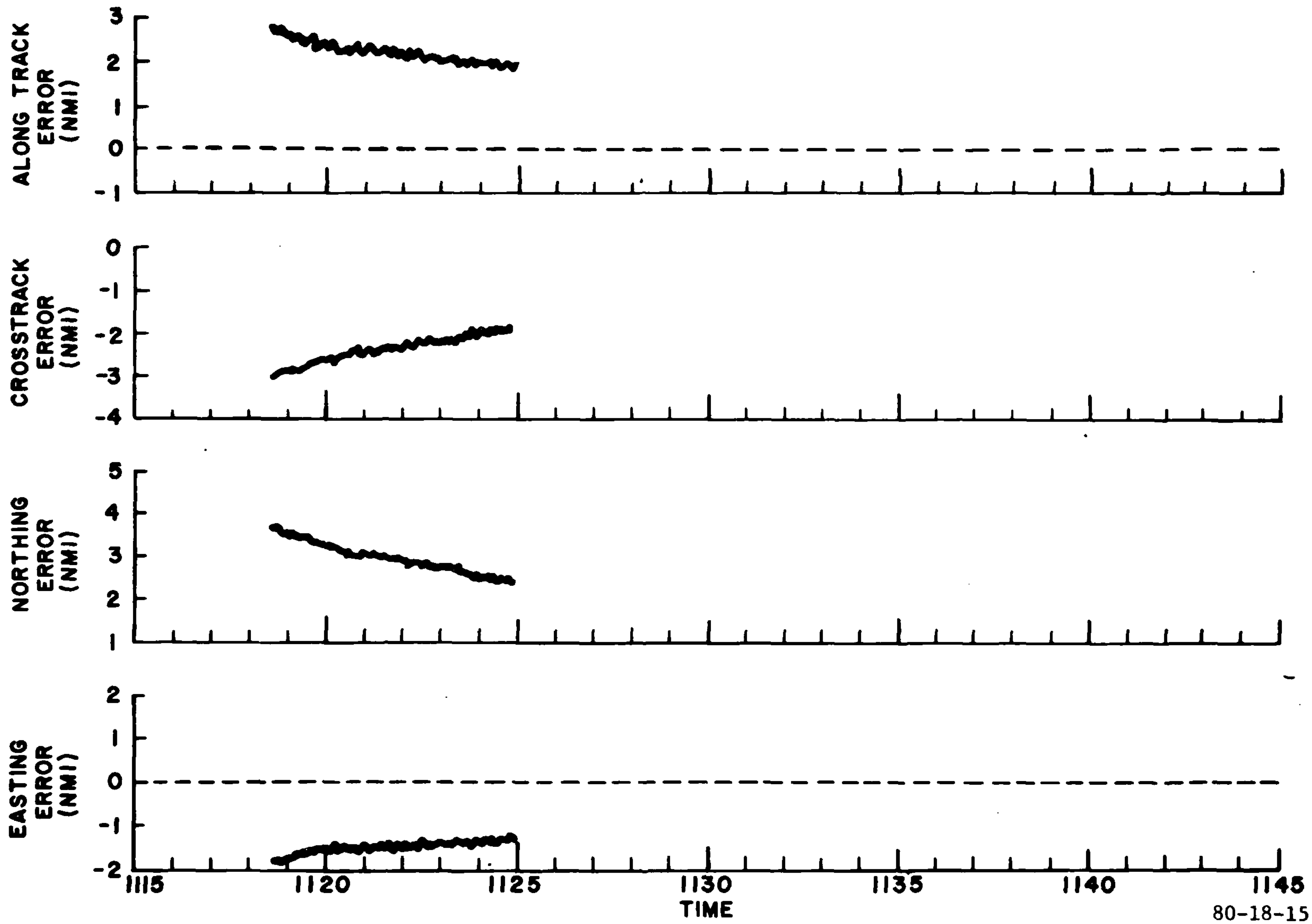


FIGURE 15. ERROR PLOTS FOR WESTERN TEST AREA, SABINE PASS (PHI HELIPORT) TO WEST CAMERON BLOCK NO. 45-4, MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

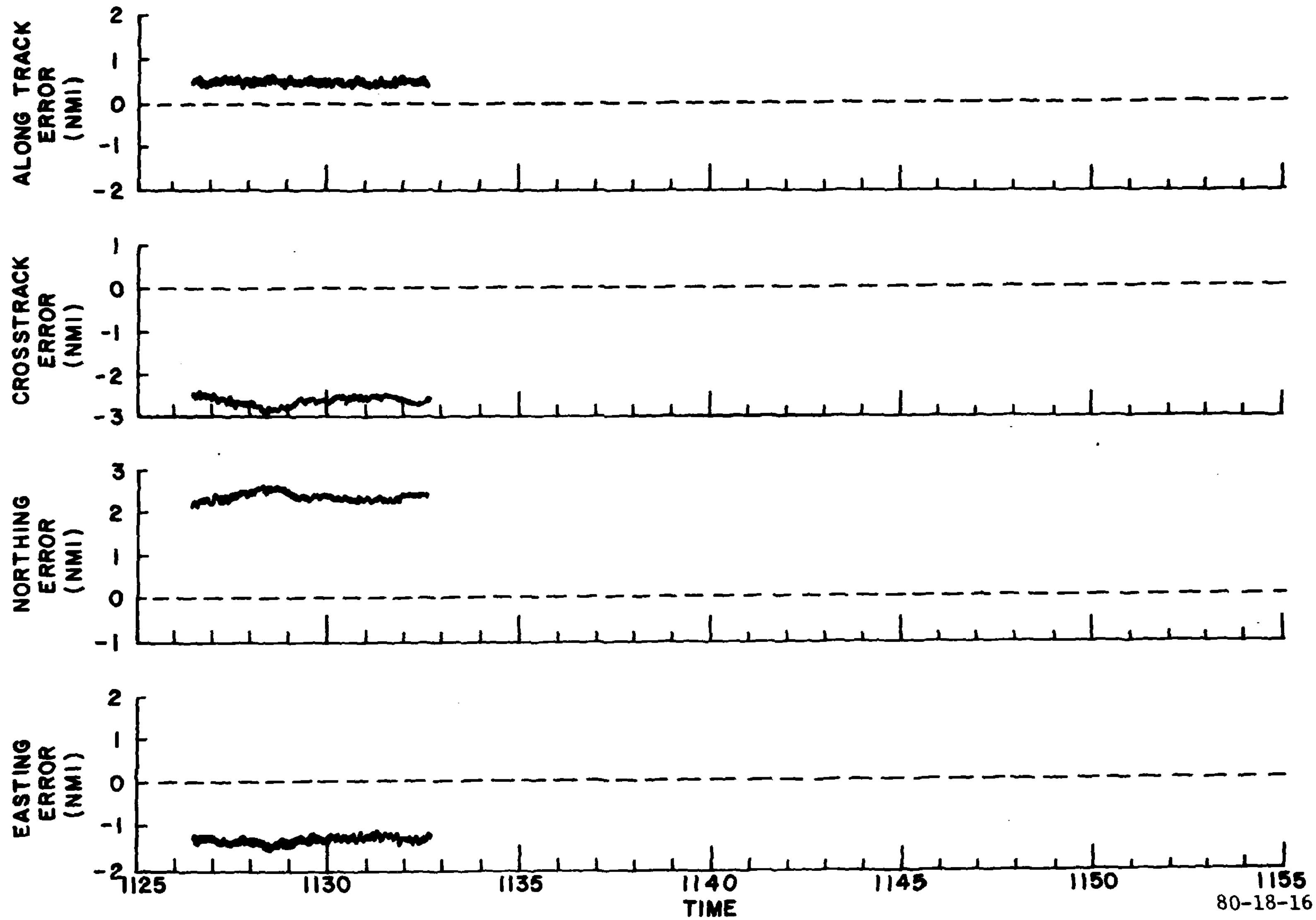


FIGURE 16. ERROR PLOTS FOR WESTERN TEST AREA, WEST CAMERON BLOCK NO. 45-4, TO CAMERON (PHI HELIPORT), MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

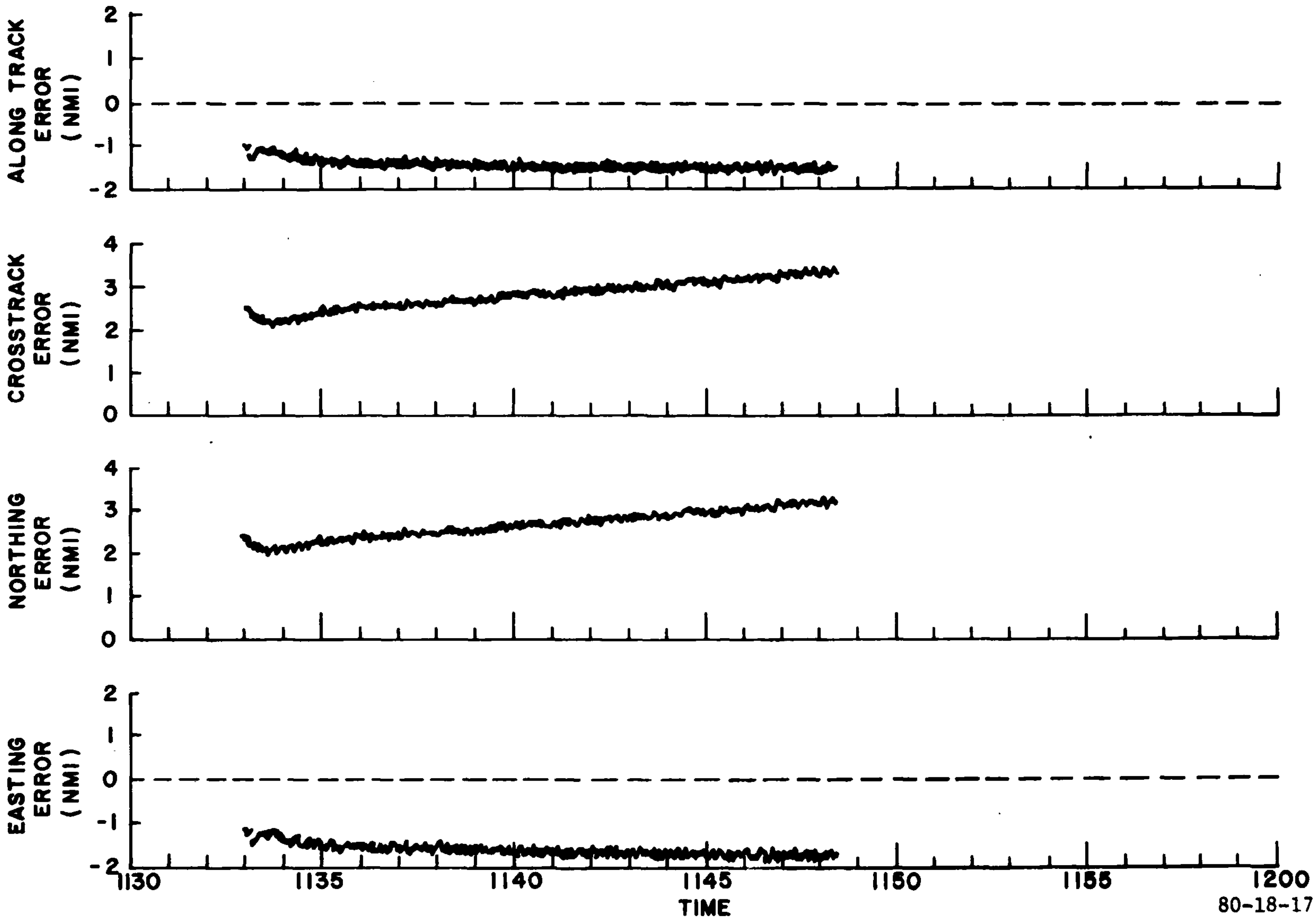


FIGURE 17. ERROR PLOTS FOR WESTERN TEST AREA, CAMERON (PHI HELIPORT) TO SABINE PASS VOR, MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

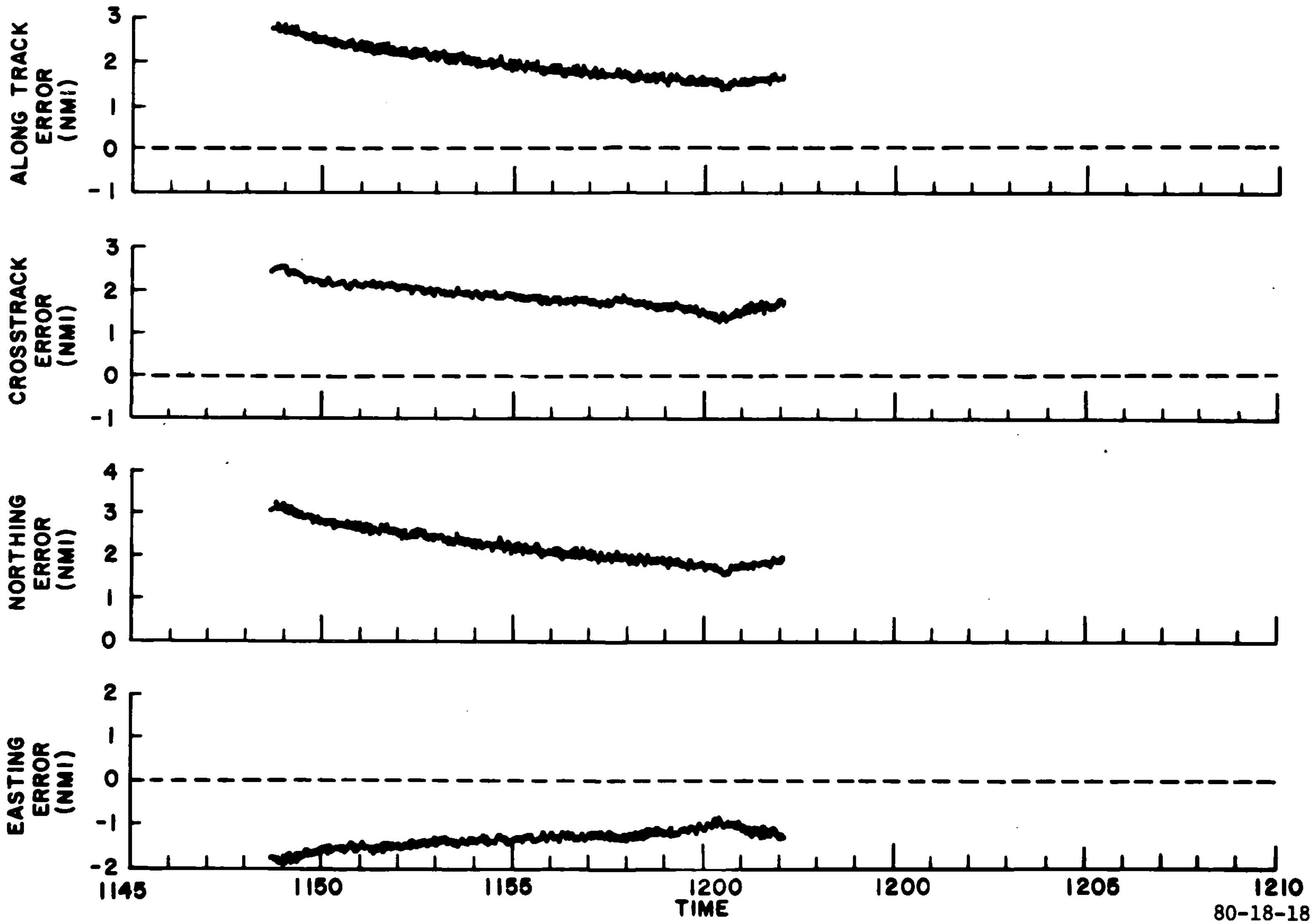


FIGURE 18. ERROR PLOTS FOR WESTERN TEST AREA, SABINE PASS VOR TO HIGH ISLAND BLOCK NO. 136, PLATFORM A, MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

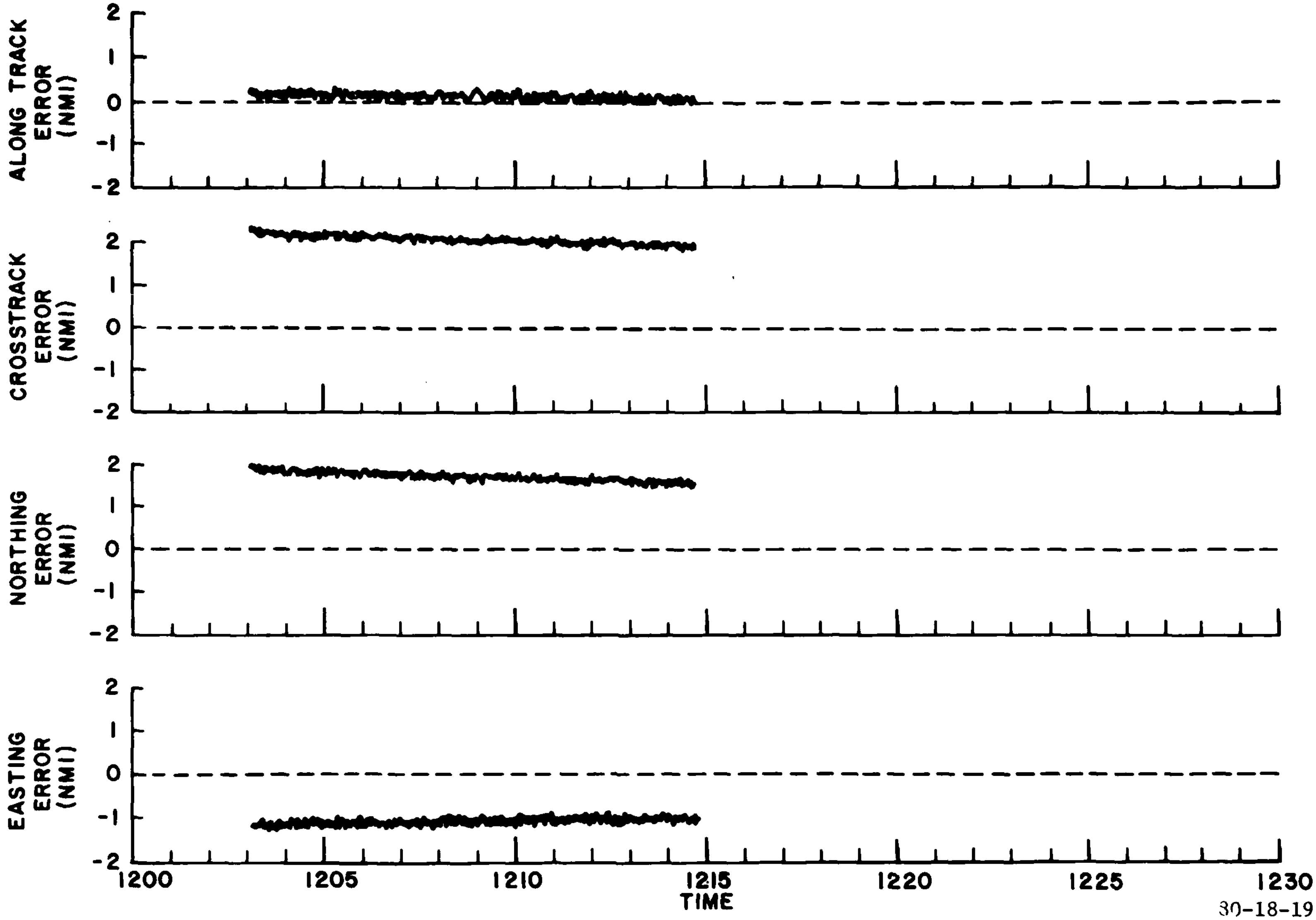


FIGURE 19. ERROR PLOTS FOR WESTERN TEST AREA, HIGH ISLAND BLOCK NO. 136, PLATFORM A, TO GALVESTON BLOCK NO. 296, MALONE, RAYMONDVILLE, GRANGEVILLE TRIAD

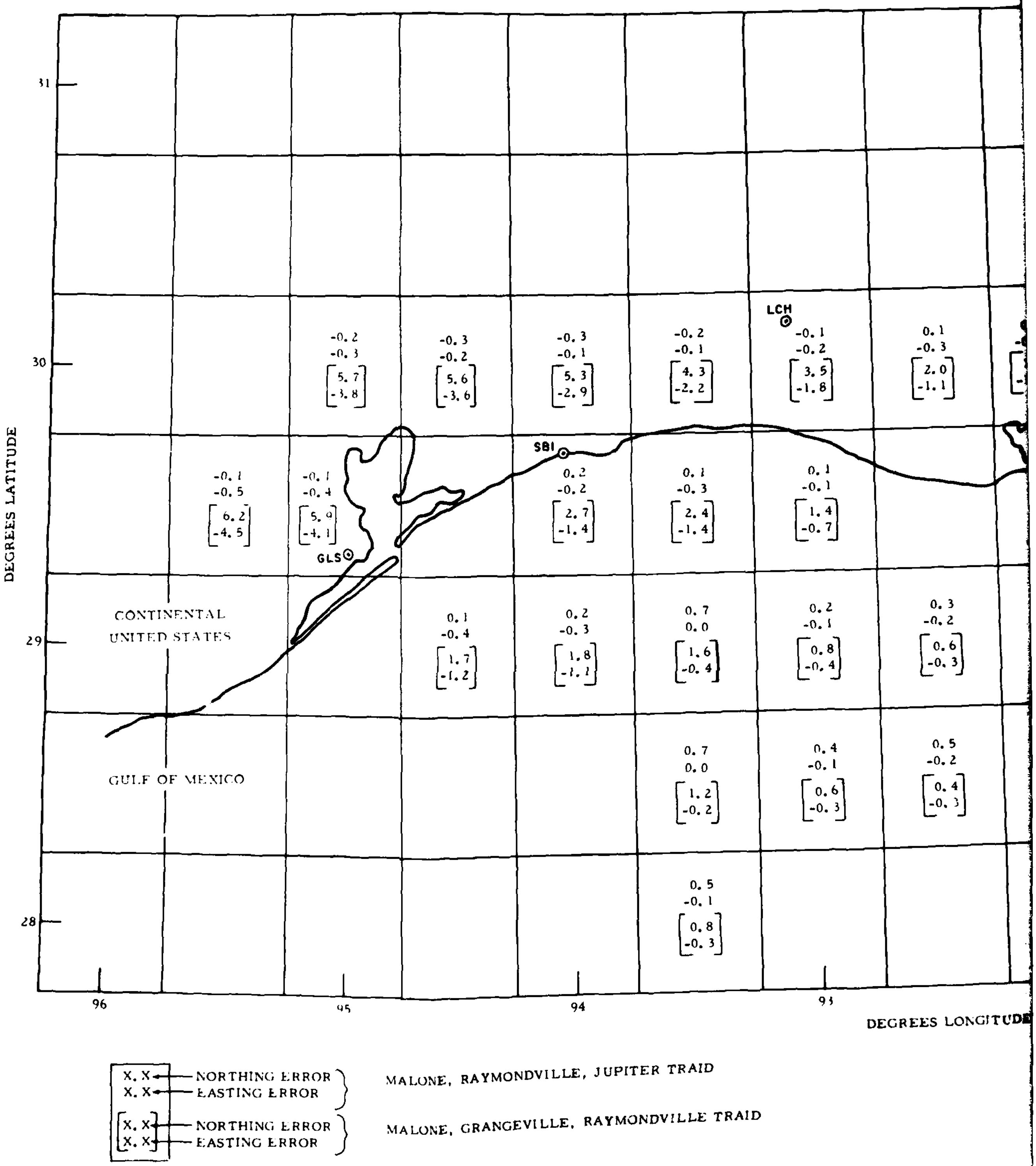
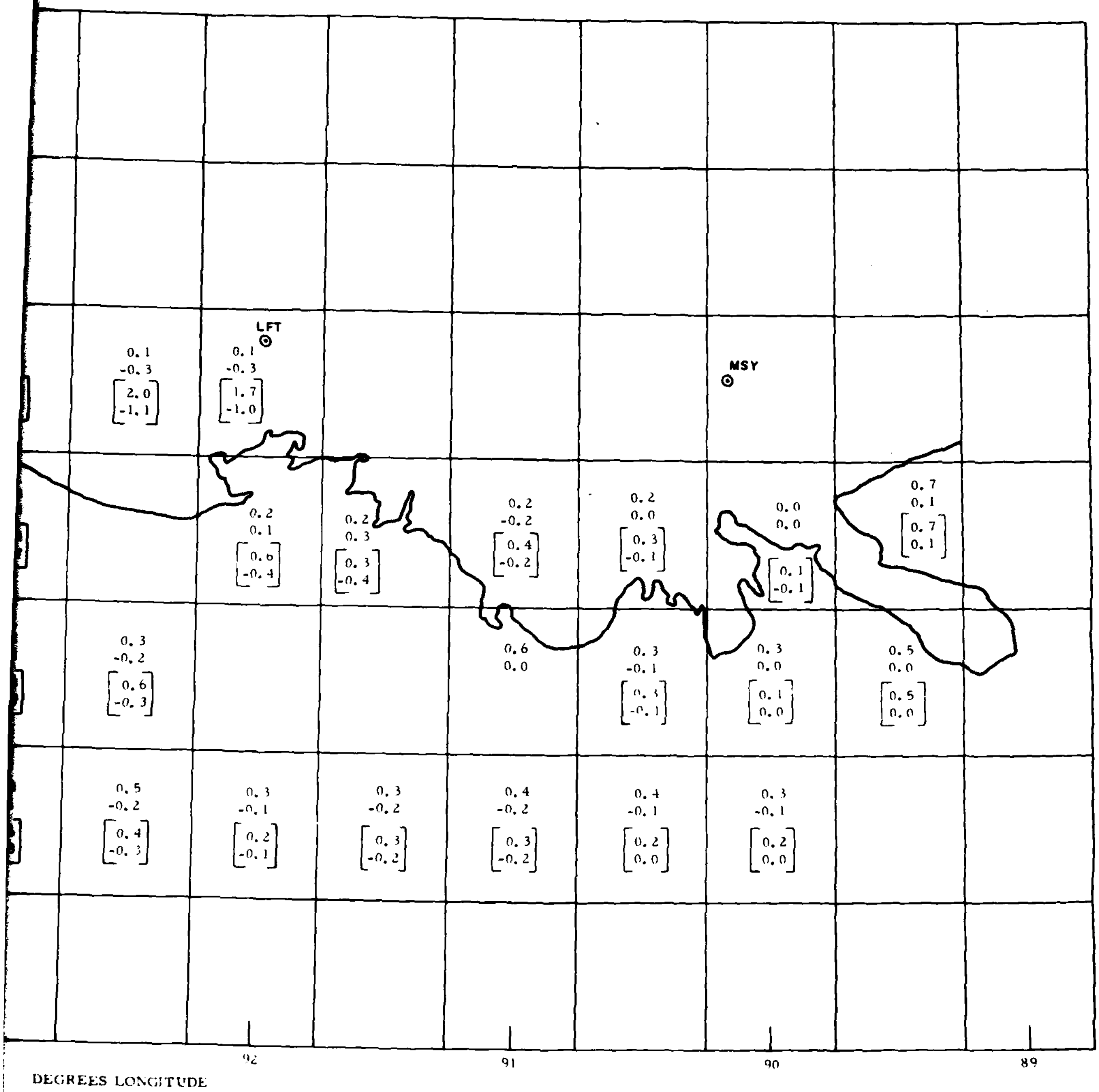


FIGURE 20. COMPOSITE NORTHING AND EASTING MEAN ERR
RAYMONDVILLE, JUPITER TRIAD AND THE MAL



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EASTING MEAN ERRORS IN NAUTICAL MILES FOR THE MALONE, RIAD AND THE MALONE, GRANGEVILLE, RAYMONDVILLE TRIAD

2

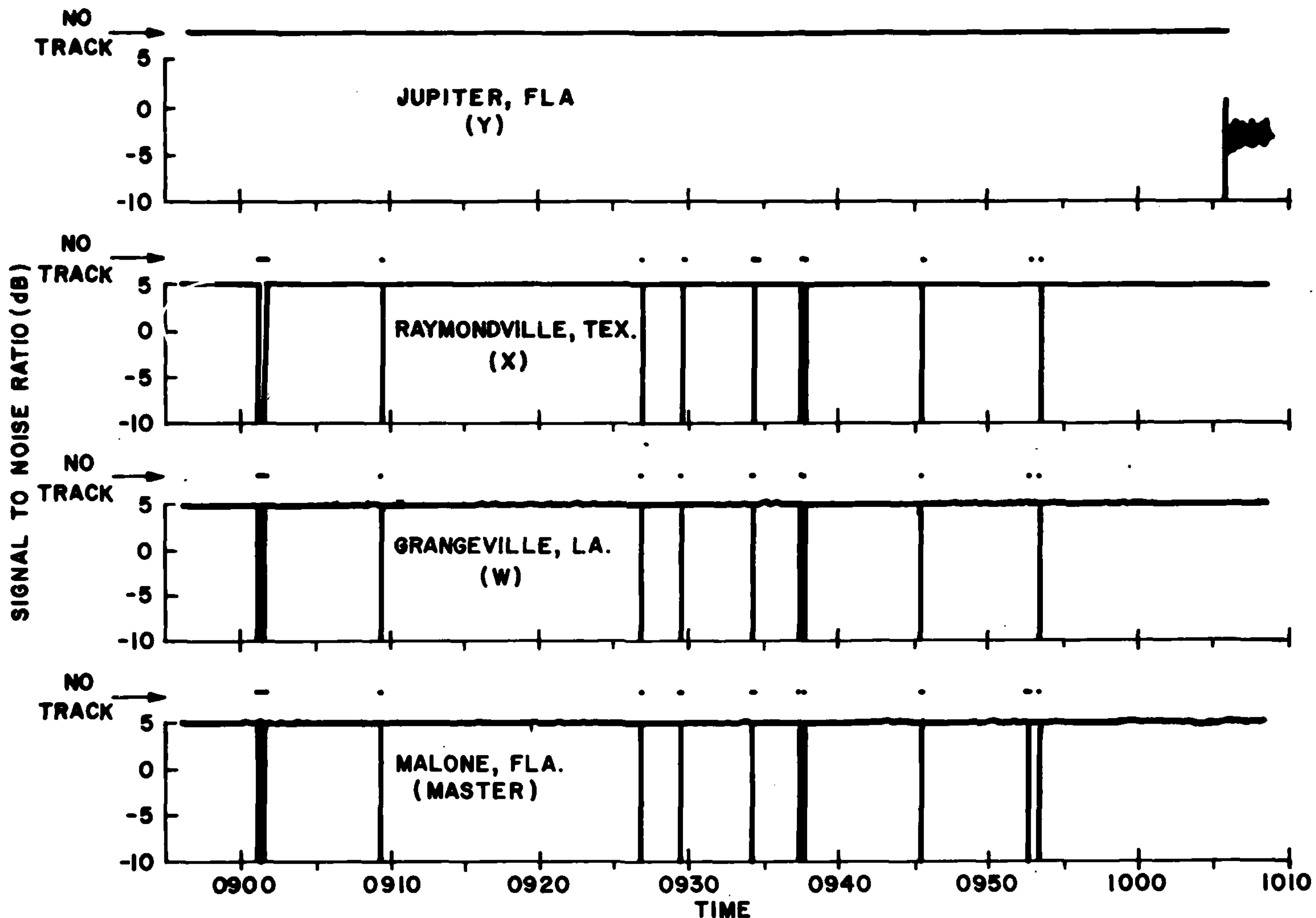

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FIGURE 21. SAMPLE SIGNAL TO NOISE PLOT FOR STATIONS IN THE SOUTHEAST U.S. CHAIN

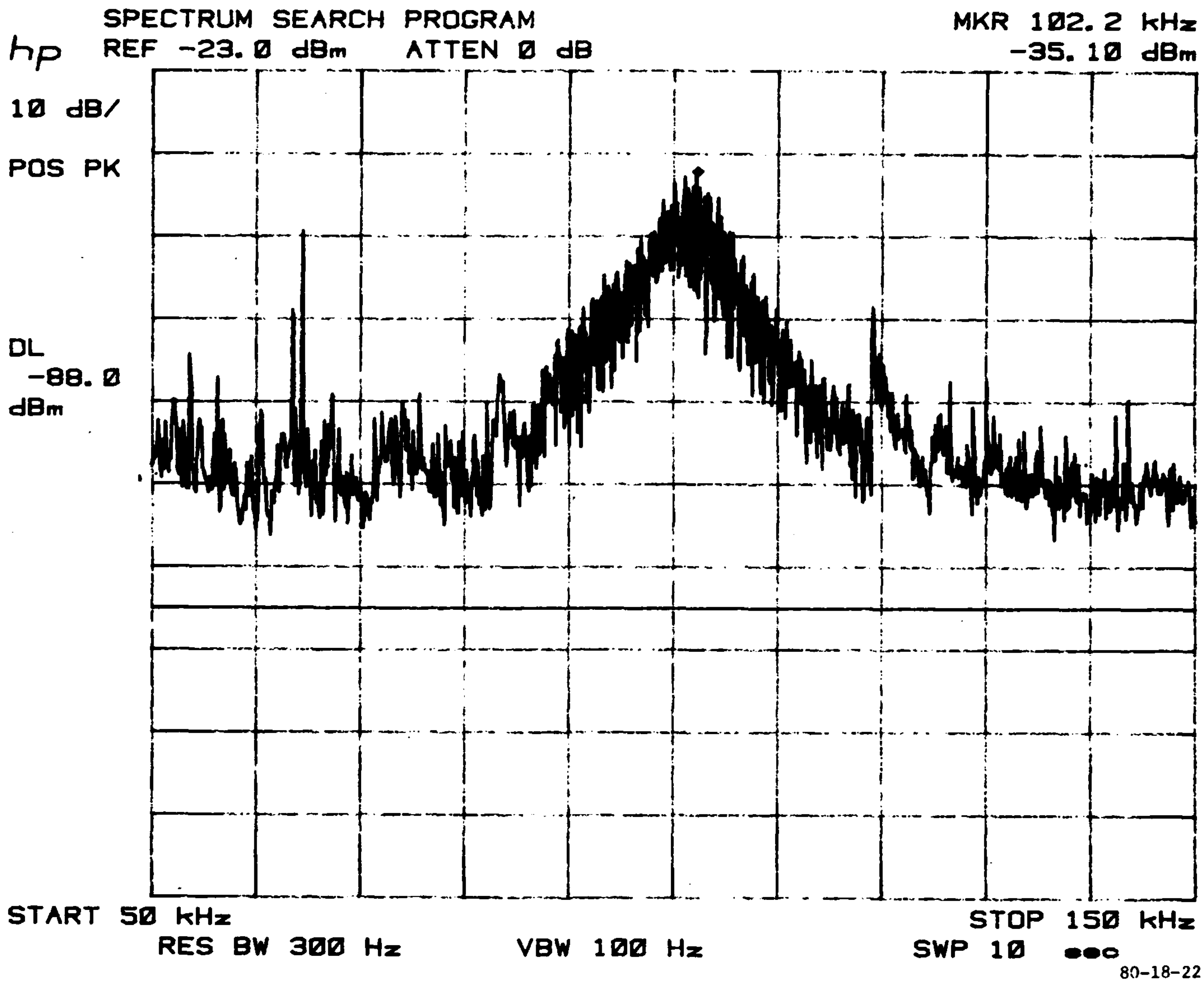

FIGURE 22. SPECTRUM SEARCH PLOT DURING WESTERN TEST AREA DATA FLIGHT

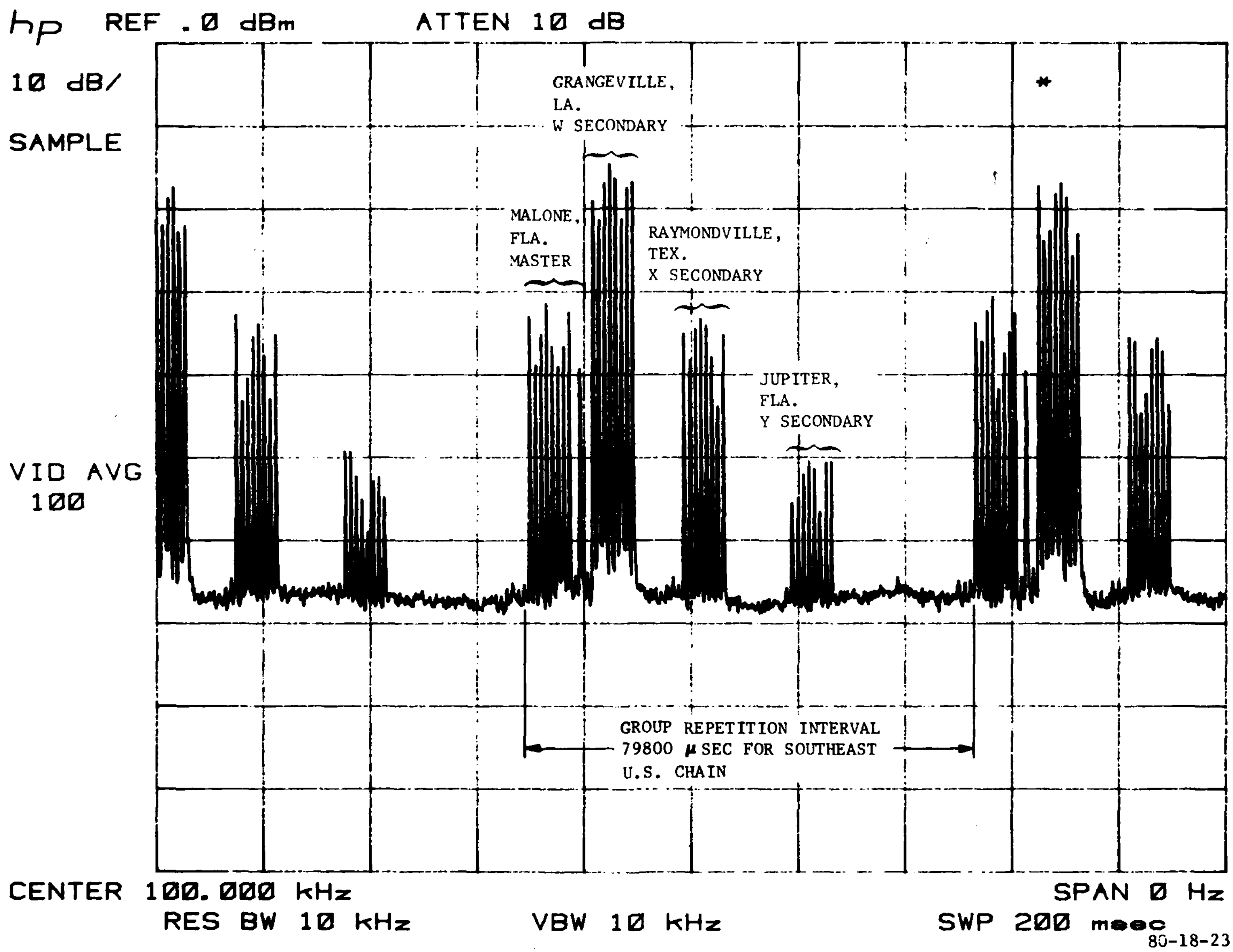

FIGURE 23. SINGLE 200 ms SWEEP AT 100 kHz DURING CENTRAL TEST AREA DATA FLIGHT

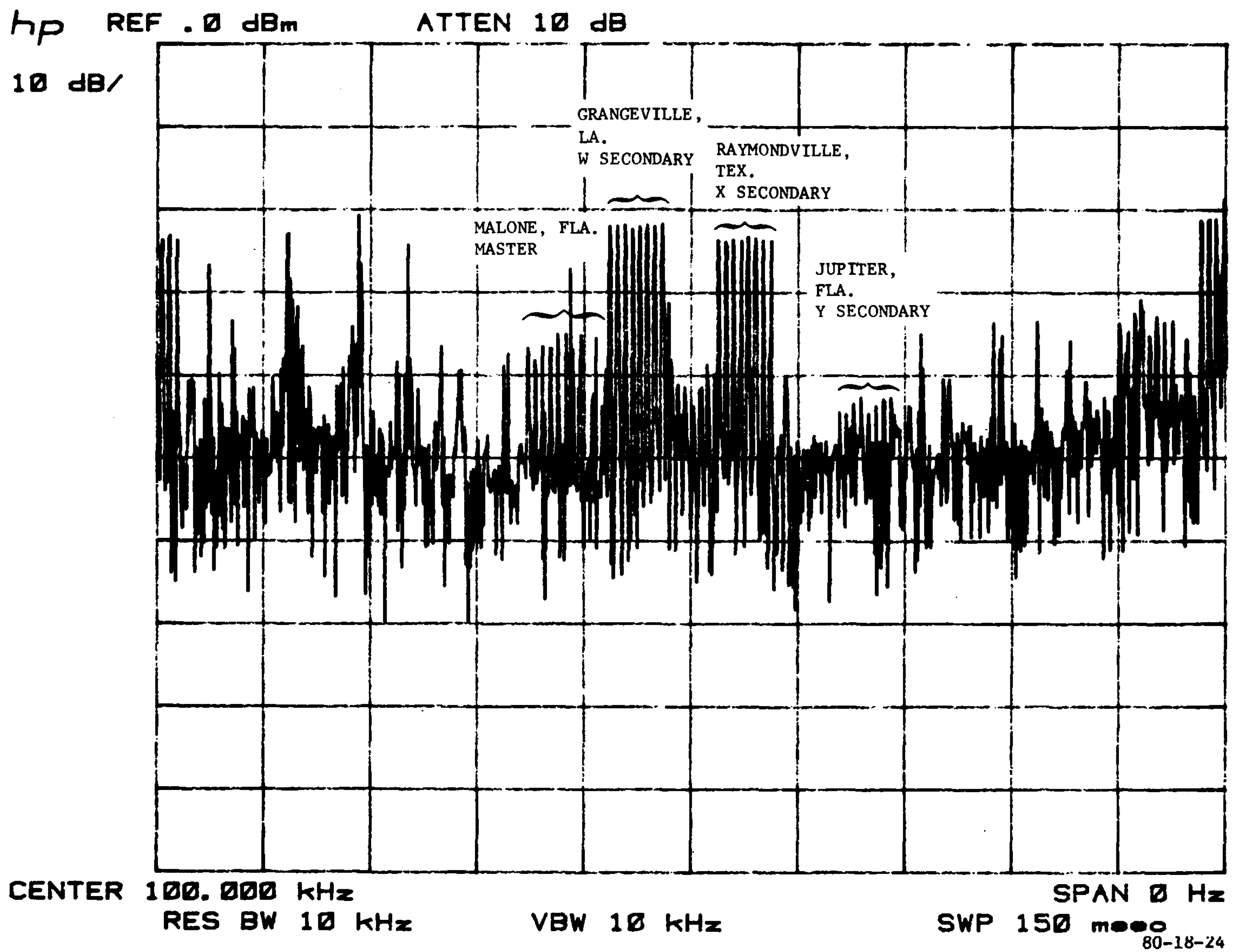

FIGURE 24. SINGLE 200 ms SWEEP AT 100 kHz WHILE ON GROUND AT HOBBY AIRPORT, HOUSTON, TEXAS

TABLE 1. LIST OF WAYPOINTS FOR EASTERN TEST AREA FLIGHT

Gulf Of Mexico LORAN-C Evaluation

W/P No.	Ident	Lat N	Long W	Freq. (kHz)	Waypoint Descriptions
1	LKM	30-11-33	91-52-58	362	Lake Martin Radio Beacon, 6 nmi E. of Lafayette, La.
2	PTN	29-42-53	91-20-12	245	Patterson Radio Beacon, Morgan City Heliport
3	DULAC	29-21-59	90-43-29	---	Airway Intersection Tall Radio Tower
4	SS-154	28-41-54	91-13-54	350	Ship Shoal Block No. 154, Radio Beacon on Platform D, Ident XSS
5	SS-214	28-30-50	90-53-07	---	Ship Shoal Block No. 214, Platform G-10
6	ST-151	28-37-02	90-14-58	---	South Timbalier Block No. 151, Platform 151G
7	DULAC	29-21-59	90-43-29	---	Airway Intersection, Tall Radio Tower
8	GNI	29-11-30	90-04-30	236	Grand Island Radio Beacon, PHI Heliport
9	ST-151	28-37-02	90-14-58	---	South Timbalier Block No. 151, Platform 151G
10	VEN	29-16-00	89-20-30	---	Venice, PHI Heliport
11	GI-43	29-00-02	89-51-32	---	Grand Island Block No. 43, Platform 43Q/AA
12	GI-47	28-56-44	90-01-52	---	Grand Island Block No. 47, Platform 47A/Qtrs.
13	GNI	29-11-30	90-04-30	236	Grand Island Radio Beacon, PHI Heliport
14	HUM	29-37-01	90-39-39	219	Houma Radio Beacon, Houma Airport, La.
15	PTN	29-42-53	91-20-12	245	Patterson Radio Beacon, Morgan City Heliport
16	LKM	30-11-33	91-52-58	362	Lake Martin Radio Beacon, 6 nmi E. of Lafayette, La.

TABLE 2. LIST OF WAYPOINTS FOR CENTRAL TEST AREA FLIGHT

Gulf Of Mexico LORAN-C Evaluation

W/P No.	Ident	Lat N	Long W	Freq. (kHz)	Waypoint Descriptions
1	LKM	30-11-33	91-52-58	362	Lake Martin Radio Beacon, 6 nmi E. of Lafayette, La.
2	PTN	29-42-53	91-20-12	245	Morgan City Patterson Radio Beacon
3	SS-28	29-06-41	91-09-40	---	Ship Shoal Block No. 28, Platform 28A-Comp.
4	SS-154	29-41-54	91-13-54	---	Ship Shoal Block No. 154, Platform D
5	EI-330	28-13-35	91-41-05	382	Eugene Island Block No. 330, NDB-EQN - Platform C
6	V-245	28-35-06	92-27-00	350	Vermilion Block No. 245, NDB-XSS Platform B
7	SS-154	29-41-54	91-13-54	---	Ship Shoal Block No. 154, Platform D
8	ICC	29-47-36	92-08-42	---	Intracoastal City PHI Heliport
9	V-149	259-18	92-17-52	---	Vermilion Block No. 149, Yellow Comp. Platform
10	V-245	28-35-06	92-27-00	350	Vermilion Block No. 245, NDB-XSS-Platform B
11	SMI-23	28-52-36	91-53-54	---	South Marsh Island Block No. 23, Quarters Platform, SMI 23A
12	PTN	29-42-53	91-20-12	245	Patterson Radio Beacon, Morgan City Heliport
13	LKM	30-11-33	91-52-58	362	Lake Martin Radio Beacon, 6 nmi E. of Lafayette

TABLE 3. LIST OF WAYPOINTS FOR WESTERN TEST AREA FLIGHT

Gulf Of Mexico LORAN-C Evaluation

W/P No.	Ident	Lat N	Long W	Freq. (kHz)	Waypoint Descriptions
1	LKM	30-11-33	91-52-58	362	Lake Martin Radio Beacon, 6 nmi E. of Lafayette, La.
2	ICC	29-47-36	92-08-42	---	Intracoastal City, La. PHI Heliport
3	CAM	29-44-54	93-21-30	---	Cameron, La. PHI Heliport
4	EC-64	20-23-50	92-59-10	---	East Cameron Block No. 64, Platform 64A
5	V-245	28-35-06	92-27-00	350	Vermilion Block No. 245, NDB-XSS-Platform B
6	EC-261	28-28-18	92-54-54	---	East Cameron Block No.270, Platform 261A
7	WC-587	28-09-39	93-20-57	341	West Cameron Block No. 587, NDB-CAJ-Platform A
8	SBI	24-44-00	93-52-42	---	Sabine Pass, La. PHI Heliport
9	WC-45	29-40-12	93-36-32	---	West Cameron Block No. 45, Platform WC-45-4
10	CAM	29-44-54	93-21-30	---	Cameron, La. PHI Heliport
11	SBI	29-41-11	94-02-16	115.4	Sabine Pass, La. VTAC-SBI
12	HI-136	29-14-35	94-09-00	---	High Island Block No. 136, Platform 136A
13	G-296	28-51-05	94-42-30	---	Galveston Block No. 296, Platform 296B
14	GLS	29-20-01	94-45-22	206	Galveston Radio Beacon, Galveston, Texas
15	HUB	29-39-00	95-16-44	117.6	Hobby VTAC Huston, Texas

TABLE 4. LIST OF AIRBORNE PARAMETERS COLLECTED

<u>Inertial Navigation System</u>

Latitude

Longitude

Ground Speed

True Heading

Track Angle

<u>LORAN-C (2 Systems)</u>

Present Position Latitude	Singal-to-Noise Ratios
Present Position Longitude	Envelope Numbers
Delta Latitude	Crosstrack Distance
Delta Longitude	Distance to Waypoint
Time Difference A	"From" Latitude
Time Difference B	"From" Longitude
Track Status	"To" Latitude
LORAN Flags	"To" Longitude

<u>Time</u>

Hours, Minutes, Seconds

TABLE 5. AC-90-45A TOTAL SYSTEM ERROR CRITERIA

Airspace	Crosstrack (nmi)	Along track (nmi)
En Route	2.5	1.5
Terminal	1.5	1.1
Approach	0.6	0.3

TABLE 6. AC-90-45A FLIGHT TECHNICAL ERROR CRITERIA

Airspace	Flight Technical Error (nmi)
En Route	2.0
Terminal	1.0
Approach	0.5

TABLE 7. STATISTICS FOR EASTERN TEST AREA, MORGAN CITY TO DULAC

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Malone, Raymondville, Jupiter Triad			
Northing	0.16	0.05	420
Easting	-0.12	0.06	420
Along Track	0.20	0.05	420
Crosstrack	-0.06	0.06	420
Malone, Grangeville, Raymondville Triad			
Northing	0.43	0.08	758
Easting	-0.22	0.05	758
Along Track	0.42	0.05	758
Crosstrack	-0.24	0.08	758

TABLE 8. STATISTICS FOR EASTERN TEST AREA, DULAC TO SHIP SHOAL BLOCK NO. 154, PLATFORM D

Malone, Grangeville, Raymondville Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.22	0.05	978
Easting	-0.31	0.10	978
Along Track	0.01	0.08	978
Crosstrack	0.38	0.07	978

TABLE 9. STATISTICS FOR EASTERN TEST AREA, SHIP SHOAL BLOCK NO. 154, PLATFORM D, TO SHIP SHOAL BLOCK NO. 214, PLATFORM G-10

Malone, Grangeville, Raymondville Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.38	0.04	154
Easting	-0.09	0.05	154
Along Track	0.28	0.05	154
Crosstrack	-0.28	0.04	154

TABLE 10. STATISTICS FOR EASTERN TEST AREA, SHIP SHOAL BLOCK NO. 214, PLATFORM G-10, TO SOUTH TIMBALIER BLOCK NO. 151, PLATFORM G

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.38	0.07	578
Easting	-0.05	0.06	578
Along Track	-0.02	0.05	578
Crosstrack	-0.38	0.08	578
	Malone, Grangeville, Raymondville Triad		
Northing	0.31	0.08	653
Easting	-0.03	0.07	653
Along Track	-0.03	0.06	653
Crosstrack	-0.31	0.08	653

TABLE 11. STATISTICS FOR EASTERN TEST AREA, SOUTH TIMBALIER BLOCK NO. 151, PLATFORM G, TO DULAC

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
	Malone, Raymondville, Jupiter Triad		
Northing	0.27	0.08	757
Easting	-0.10	0.05	757
Along Track	-0.28	0.09	757
Crosstrack	0.04	0.05	757
	Malone, Grangeville, Raymondville Triad		
Northing	0.28	0.05	529
Easting	-0.11	0.05	529
Along Track	-0.29	0.05	529
Crosstrack	0.04	0.05	529

TABLE 12. STATISTICS FOR EASTERN TEST AREA, DULAC TO GRAND ISLAND

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
	Malone, Raymondville, Jupiter Triad		
Northing	0.08	0.08	549
Easting	0.04	0.07	549
Along Track	-0.02	0.08	549
Crosstrack	-0.09	0.07	549
	Malone, Grangeville, Raymondville Triad		
Northing	0.17	0.11	487
Easting	0.00	0.07	487
Along Track	0.05	0.09	487
Crosstrack	-0.17	0.10	487

TABLE 13. STATISTICS FOR EASTERN TEST AREA, GRAND ISLAND TO SOUTH TIMBALIER BLOCK NO. 151, PLATFORM G

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Malone, Raymondville, Jupiter Triad			
Northing	0.11	0.08	602
Easting	-0.15	0.05	602
Along Track	0.07	0.08	602
Crosstrack	0.17	0.04	602
Malone, Grangeville, Raymondville Triad			
Northing	0.04	0.07	681
Easting	-0.11	0.06	681
Along Track	0.00	0.08	681
Crosstrack	0.12	0.05	681

TABLE 14. STATISTICS FOR EASTERN TEST AREA, SOUTH TIMBALIER BLOCK NO. 151, PLATFORM G, TO VENICE

Malone, Grangeville, Raymondville Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.55	0.17	882
Easting	0.03	0.06	882
Along Track	0.20	0.07	882
Crosstrack	-0.52	0.17	882

TABLE 15. STATISTICS FOR EASTERN TEST AREA, VENICE TO GRAND ISLAND BLOCK NO. 43, PLATFORM Q/AA

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.51	0.10	628
Easting	-0.01	0.05	628
Along Track	-0.44	0.08	628
Crosstrack	0.26	0.07	628
Malone, Grangeville, Raymondville Triad			
Northing	0.48	0.08	667
Easting	0.01	0.04	667
Along Track	-0.40	0.07	667
Crosstrack	0.26	0.07	667

TABLE 16. STATISTICS FOR EASTERN TEST AREA, GRAND ISLAND BLOCK NO. 43, PLATFORM Q/AA, TO GRAND ISLAND BLOCK NO. 47, PLATFORM A

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.42	0.05	177
Easting	-0.04	0.04	177
Along Track	0.11	0.04	177
Crosstrack	0.41	0.05	177
Malone, Grangeville, Raymondville Triad			
Northing	0.37	0.05	179
Easting	-0.01	0.04	179
Along Track	0.12	0.04	179
Crosstrack	0.36	0.05	179

TABLE 17. STATISTICS FOR EASTERN TEST AREA, GRAND ISLAND BLOCK NO. 47, PLATFORM A, TO GRAND ISLAND RADIO BEACON

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.28	0.08	314
Easting	0.04	0.06	314
Along Track	-0.27	0.08	314
Crosstrack	0.08	0.06	314

TABLE 18. STATISTICS FOR EASTERN TEST AREA, THREE MILE ORBIT OF GRAND ISLAND RADIO BEACON

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.00	0.09	479
Easting	0.12	0.10	479
Along Track	0.01	0.09	479
Crosstrack	0.12	0.10	479
Malone, Grangeville, Raymondville Triad			
Northing	-0.02	0.10	717
Easting	0.09	0.12	717
Along Track	0.03	0.10	717
Crosstrack	0.09	0.11	717

TABLE 19. STATISTICS FOR EASTERN TEST AREA, GRAND ISLAND RADIO BEACON TO HOUMA

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.05	0.04	197
Easting	-0.01	0.06	197
Along Track	-0.04	0.06	197
Crosstrack	0.03	0.05	197

Malone, Grangeville, Raymondville Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.12	0.05	198
Easting	-0.03	0.07	198
Along Track	-0.10	0.08	198
Crosstrack	0.07	0.04	198

TABLE 20. STATISTICS FOR EASTERN TEST AREA, HOUMA TO MORGAN CITY

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.23	0.04	523
Easting	-0.10	0.05	523
Along Track	-0.13	0.05	523
Crosstrack	0.21	0.05	523

Malone, Grangeville, Raymondville Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.45	0.04	532
Easting	-0.18	0.05	532
Along Track	-0.26	0.05	532
Crosstrack	0.41	0.04	532

TABLE 21. STATISTICS FOR CENTRAL TEST AREA, LAKE MARTIN RADIO BEACON TO MORGAN CITY

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.47	0.06	34
Easting	-0.22	0.05	34
Along Track	0.49	0.05	34
Crosstrack	-0.17	0.06	34
Malone, Grangeville, Raymondville Triad			
Northing	0.23	0.06	36
Easting	-0.13	0.05	36
Along Track	0.25	0.05	36
Crosstrack	0.13	0.05	36

TABLE 22. STATISTICS FOR CENTRAL TEST AREA, MORGAN CITY TO SHIP SHOAL BLOCK NO. 28, PLATFORM A

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.32	0.06	227
Easting	-0.43	0.06	227
Along Track	0.41	0.05	227
Crosstrack	0.34	0.07	227
Malone, Grangeville, Raymondville Triad			
Northing	0.03	0.06	410
Easting	-0.34	0.05	410
Along Track	0.12	0.05	410
Crosstrack	0.32	0.06	410

TABLE 23. STATISTICS FOR CENTRAL TEST AREA, SHIP SHOAL BLOCK NO. 28, PLATFORM A, TO SHIP SHOAL BLOCK NO. 154, PLATFORM D

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Malone, Raymondville, Jupiter Triad			
Northing	0.32	0.04	68
Easting	-0.15	0.05	68
Along Track	-0.34	0.04	68
Crosstrack	-0.12	0.05	68
Malone, Grangeville, Raymondville Triad			
Northing	0.38	0.04	71
Easting	-0.17	0.05	71
Along Track	-0.40	0.04	71
Crosstrack	-0.13	0.05	71

TABLE 24. STATISTICS FOR CENTRAL TEST AREA, SHIP SHOAL BLOCK NO. 154, PLATFORM D, TO EUGENE ISLAND BLOCK NO. 330, PLATFORM C

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Malone, Raymondville, Jupiter Triad			
Northing	0.21	0.06	500
Easting	-0.14	0.05	500
Along Track	0.16	0.05	500
Crosstrack	0.19	0.05	500
Malone, Grangeville, Raymondville Triad			
Northing	0.31	0.06	515
Easting	-0.18	0.05	515
Along Track	0.26	0.05	515
Crosstrack	0.25	0.05	515

TABLE 25. STATISTICS FOR CENTRAL TEST AREA, EUGENE ISLAND BLOCK NO. 330, PLATFORM C, TO VERMILION BLOCK NO. 245, PLATFORM B

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.37	0.06	826
Easting	-0.14	0.07	826
Along Track	-0.30	0.08	826
Crosstrack	0.26	0.04	826
Malone, Grangeville, Raymondville Triad			
Northing	0.36	0.06	840
Easting	-0.14	0.05	840
Along Track	-0.29	0.05	840
Crosstrack	0.25	0.06	840

TABLE 26. STATISTICS FOR CENTRAL TEST AREA, VERMILION BLOCK NO. 245, PLATFORM B, TO SHIP SHOAL BLOCK NO. 154, PLATFORM D

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.41	0.11	1180
Easting	-0.10	0.14	1180
Along Track	-0.22	0.17	1180
Crosstrack	-0.35	0.07	1180
Malone, Grangeville, Raymondville Triad			
Northing	0.26	1.24	1182
Easting	-0.07	0.23	1182
Along Track	-0.13	0.79	1182
Crosstrack	-0.23	0.98	1182

TABLE 27. STATISTICS FOR CENTRAL TEST AREA, SHIP SHOAL BLOCK NO. 154, PLATFORM D, TO INTRACOASTAL CITY

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Malone, Raymondville, Jupiter Triad			
Northing	0.39	0.27	1045
Easting	-0.65	0.16	1045
Along Track	-0.69	0.14	1045
Crosstrack	0.31	0.28	1045
Malone, Grangeville, Raymondville Triad			
Northing	0.17	0.35	1014
Easting	-0.46	0.79	1014
Along Track	-0.48	0.75	1014
Crosstrack	0.12	0.44	1014

TABLE 28. STATISTICS FOR CENTRAL TEST AREA, INTRACOASTAL CITY TO VERMILION BLOCK NO. 149, COMPRESSOR PLATFORM

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Malone, Raymondville, Jupiter Triad			
Northing	0.62	0.10	796
Easting	-0.27	0.05	796
Along Track	0.57	0.10	796
Crosstrack	0.37	0.06	796
Malone, Grangeville, Raymondville Triad			
Northing	0.23	0.05	888
Easting	-0.11	0.07	888
Along Track	0.21	0.05	888
Crosstrack	0.15	0.08	888

TABLE 29. STATISTICS FOR CENTRAL TEST AREA, VERMILION BLOCK NO. 149, COMPRESSOR PLATFORM, TO VERMILION BLOCK NO. 245, PLATFORM B

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Malone, Raymondville, Jupiter Triad			
Northing	0.58	0.05	554
Easting	-0.32	0.04	554
Along Track	0.45	0.05	554
Crosstrack	0.49	0.04	554
Malone, Grangeville, Raymondville Triad			
Northing	0.41	0.07	559
Easting	-0.25	0.05	559
Along Track	0.31	0.06	559
Crosstrack	0.37	0.06	559

TABLE 30. STATISTICS FOR WESTERN TEST AREA, LAKE MARTIN RADIO BEACON TO INTRACOASTAL CITY

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.03	0.04	22
Easting	-0.10	0.04	22
Along Track	-0.03	0.04	22
Crosstrack	0.10	0.04	22

TABLE 31. STATISTICS FOR WESTERN TEST AREA, INTRACOASTAL CITY TO CAMERON

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	-0.01	0.08	1080
Easting	-0.20	0.05	1080
Along Track	-0.20	0.05	1080
Crosstrack	0.00	0.09	1080

TABLE 32. STATISTICS FOR WESTERN TEST AREA, CAMERON TO EAST CAMERON BLOCK NO. 64, PLATFORM A

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.06	0.11	975
Easting	-0.04	0.08	975
Along Track	0.07	0.11	975
Crosstrack	-0.01	0.07	975

TABLE 33. STATISTICS FOR WESTERN TEST AREA, EAST CAMERON BLOCK NO. 64, PLATFORM A, TO VERMILION BLOCK NO. 245, PLATFORM B

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.24	0.26	981
Easting	-0.11	0.20	981
Along Track	0.26	0.16	981
Crosstrack	-0.02	0.29	981

TABLE 34. STATISTICS FOR WESTERN TEST AREA, VERMILION BLOCK NO. 245, PLATFORM B, TO EAST CAMERON BLOCK NO. 261, PLATFORM A

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.38	0.08	386
Easting	-0.31	0.09	386
Along Track	-0.20	0.09	386
Crosstrack	0.45	0.09	386

TABLE 35. STATISTICS FOR WESTERN TEST AREA, EAST CAMERON BLOCK NO. 261, PLATFORM A, TO WEST CAMERON BLOCK NO. 587, PLATFORM A

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.36	0.04	376
Easting	-0.14	0.04	376
Along Track	0.12	0.05	376
Crosstrack	0.37	0.04	376

TABLE 36. STATISTICS FOR WESTERN TEST AREA, WEST CAMERON BLOCK NO. 587, PLATFORM A, TO SABINE PASS

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.60	0.21	2061
Easting	-0.01	0.21	2061
Along Track	-0.57	0.25	2061
Crosstrack	0.16	0.17	2061

TABLE 37. STATISTICS FOR WESTERN TEST AREA, SABINE PASS TO WEST CAMERON BLOCK NO. 45-4

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.13	0.06	377
Easting	-0.19	0.09	377
Along Track	0.22	0.08	377
Crosstrack	-0.07	0.07	377

TABLE 38. STATISTICS FOR WESTERN TEST AREA, WEST CAMERON BLOCK NO. 45-5, TO CAMERON

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.09	0.09	370
Easting	-0.31	0.06	370
Along Track	0.26	0.04	370
Crosstrack	-0.20	0.10	370

TABLE 39. STATISTICS FOR WESTERN TEST AREA, CAMERON TO SABINE PASS VOR

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.02	0.21	927
Easting	-0.36	0.14	927
Along Track	-0.35	0.12	927
Crosstrack	0.05	0.21	927

TABLE 40. STATISTICS FOR WESTERN TEST AREA, SABINE PASS VOR TO HIGH ISLAND BLOCK NO. 136, PLATFORM A

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.08	0.09	800
Easting	-0.27	0.08	800
Along Track	0.02	0.08	800
Crosstrack	0.28	0.09	800

TABLE 41. STATISTICS FOR WESTERN TEST AREA, HIGH ISLAND BLOCK NO. 136, PLATFORM A, TO GALVESTON BLOCK NO. 296, PLATFORM B

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.14	0.07	655
Easting	-0.35	0.05	655
Along Track	-0.19	0.7	655
Crosstrack	0.33	0.05	655

TABLE 42. STATISTICS FOR HOUSTON TO LAFAYETTE OVERLAND FLIGHT, HOBBY VOR TO BEAUMONT VOR

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	-0.15	0.11	1883
Easting	0.37	0.17	1883
Along Track	0.40	0.14	1883
Crosstrack	0.05	0.15	1883

TABLE 43. STATISTICS FOR HOUSTON TO LAFAYETTE OVERLAND FLIGHT, BEAUMONT VOR TO LAKE CHARLES VOR

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	-0.23	0.10	1868
Easting	0.09	0.10	1868
Along Track	0.14	0.09	1868
Crosstrack	0.20	0.11	1868

TABLE 44. STATISTICS FOR HOUSTON TO LAFAYETTE OVERLAND FLIGHT, LAKE CHARLES VOR TO LAFAYETTE VOR

Malone, Raymondville, Jupiter Triad

Error	Mean (nmi)	One Std. Dev. (nmi)	Samples
Northing	0.13	0.27	1092
Easting	0.42	0.23	1092
Along Track	0.42	0.23	1092
Crosstrack	-0.14	0.26	1092

TABLE 45. MAXIMUM MEAN ERRORS—EASTERN TEST AREA

	Malone, Raymondville, Jupiter	Malone, Grangeville, Raymondville
Maximum Mean Northing Error (nmi) On Any Segment	.51	.55
Maximum Mean Easting Error (nmi) On Any Segment	-0.15	-0.31
Maximum Mean Crosstrack Error (nmi) On Any Segment	0.41	-0.52
Maximum Mean Along Track Error (nmi) On Any Segment	-0.44	0.42

TABLE 46. MAXIMUM RSS VALUE OF NORTHING AND EASTING ERRORS FOR EASTERN TEST AREA

Malone, Raymondville, Jupiter	Malone, Grangeville, Raymondville
.51	.56

TABLE 47. MAXIMUM MEAN ERRORS—CENTRAL TEST AREA

	Malone, Raymondville, Jupiter	Malone, Grangeville, Raymondville
Maximum Mean Northing Error (nmi) On Any Segment	0.62	0.41
Maximum Mean Easting Error (nmi) On Any Segment	-0.65	-0.46
Maximum Mean Crosstrack Error (nmi) On Any Segment	0.49	0.37
Maximum Mean Along Track Error (nmi) On Any Segment	-0.69	-0.48

TABLE 48. MAXIMUM RSS VALUE OF NORTHING AND EASTING ERRORS FOR CENTRAL TEST AREA

Malone, Raymondville, Jupiter	Malone, Grangeville, Raymondville
.75	.49

TABLE 49. MAXIMUM MEAN ERRORS—WESTERN TEST AREA

	Malone, Raymondville, Jupiter
Maximum Mean Northing Error (nmi) On Any Segment	0.60
Maximum Mean Easting Error (nmi) On Any Segment	-0.36
Maximum Mean Crosstrack Error (nmi) On Any Segment	0.45
Maximum Mean Along Track Error (nmi) On Any Segment	-0.57

APPENDIX A

SIGNAL-TO-NOISE RATIO PLOTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

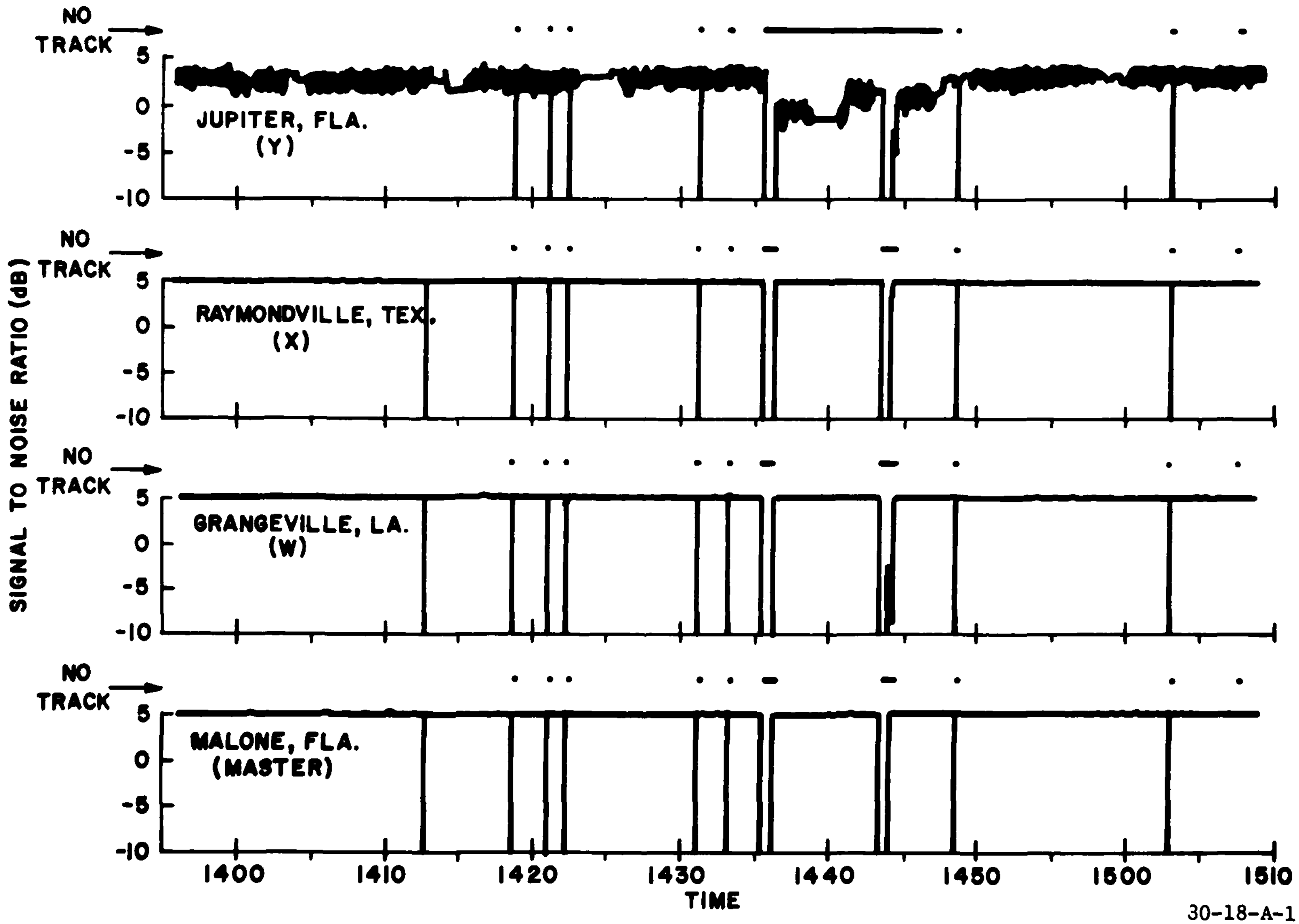

FIGURE A-1. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 1

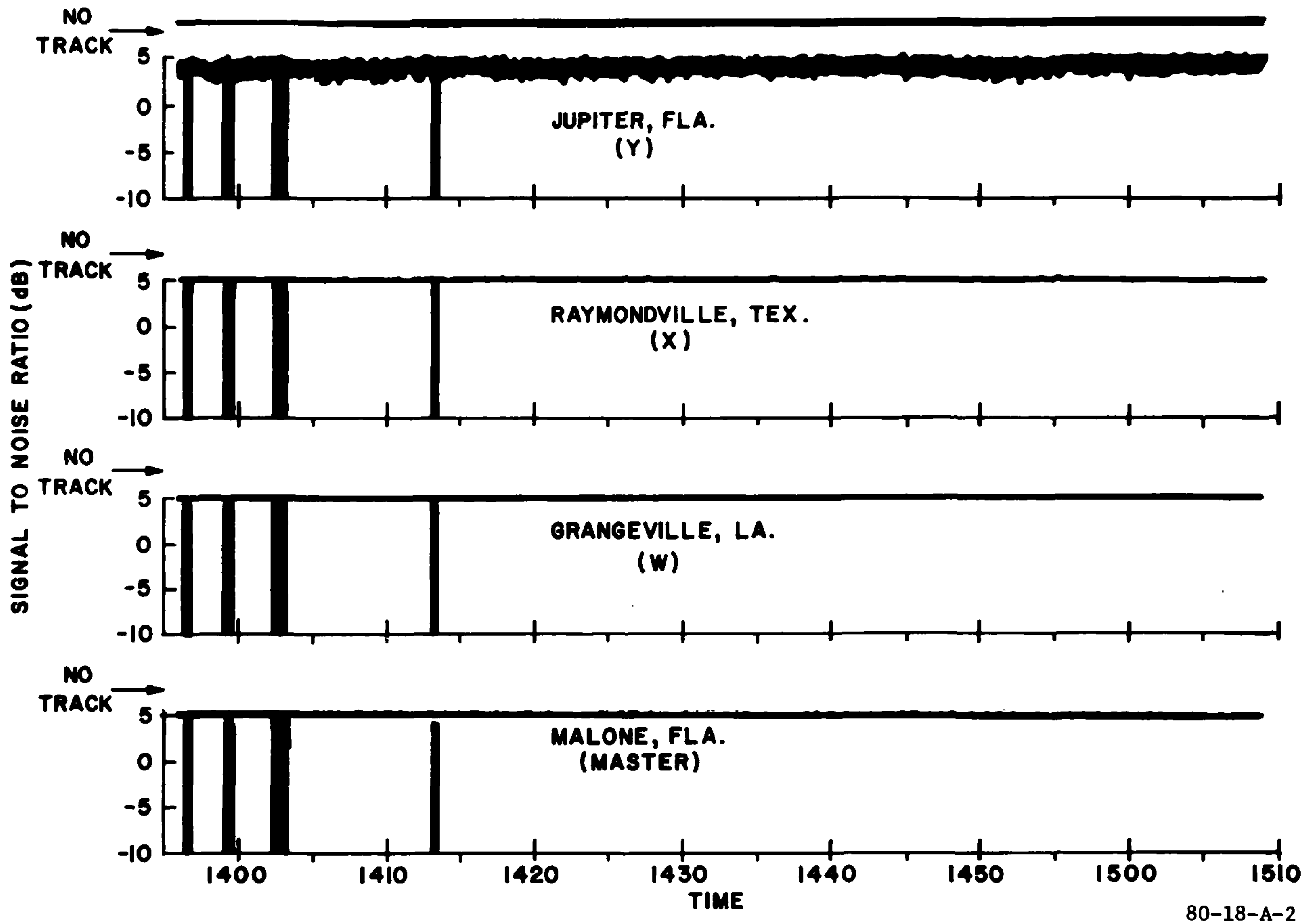

FIGURE A-2. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 2

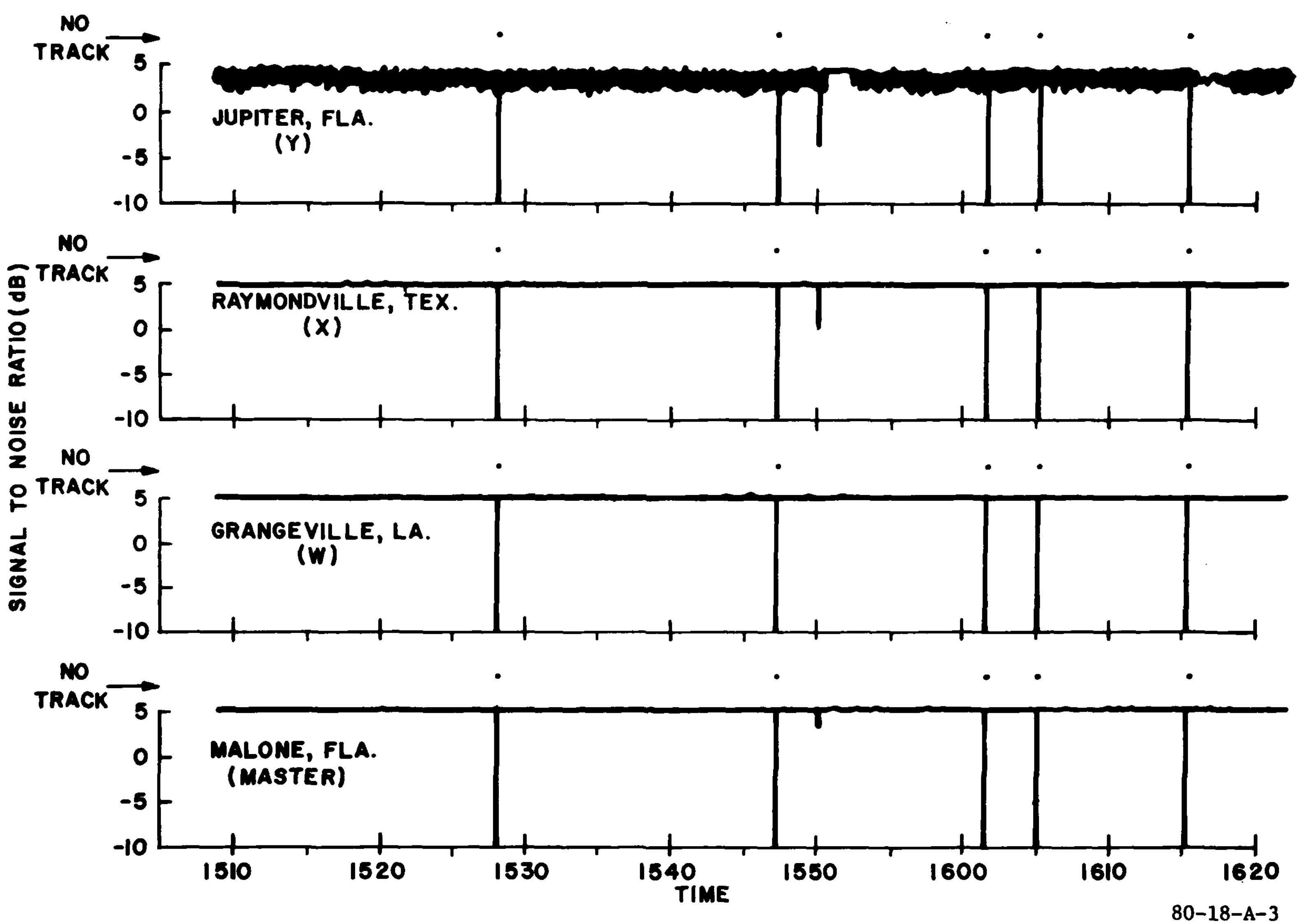

FIGURE A-3. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 1

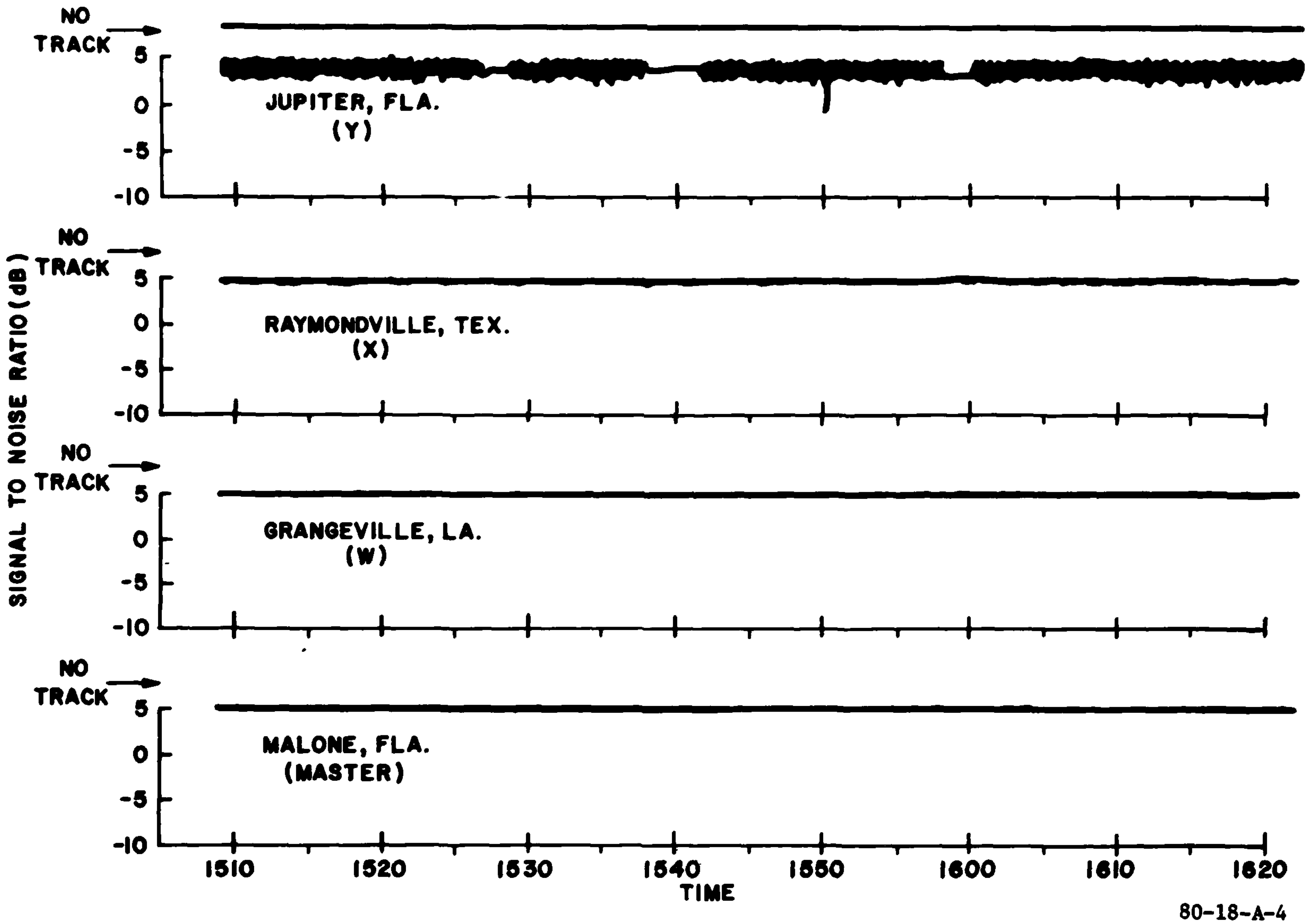

FIGURE A-4. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 2

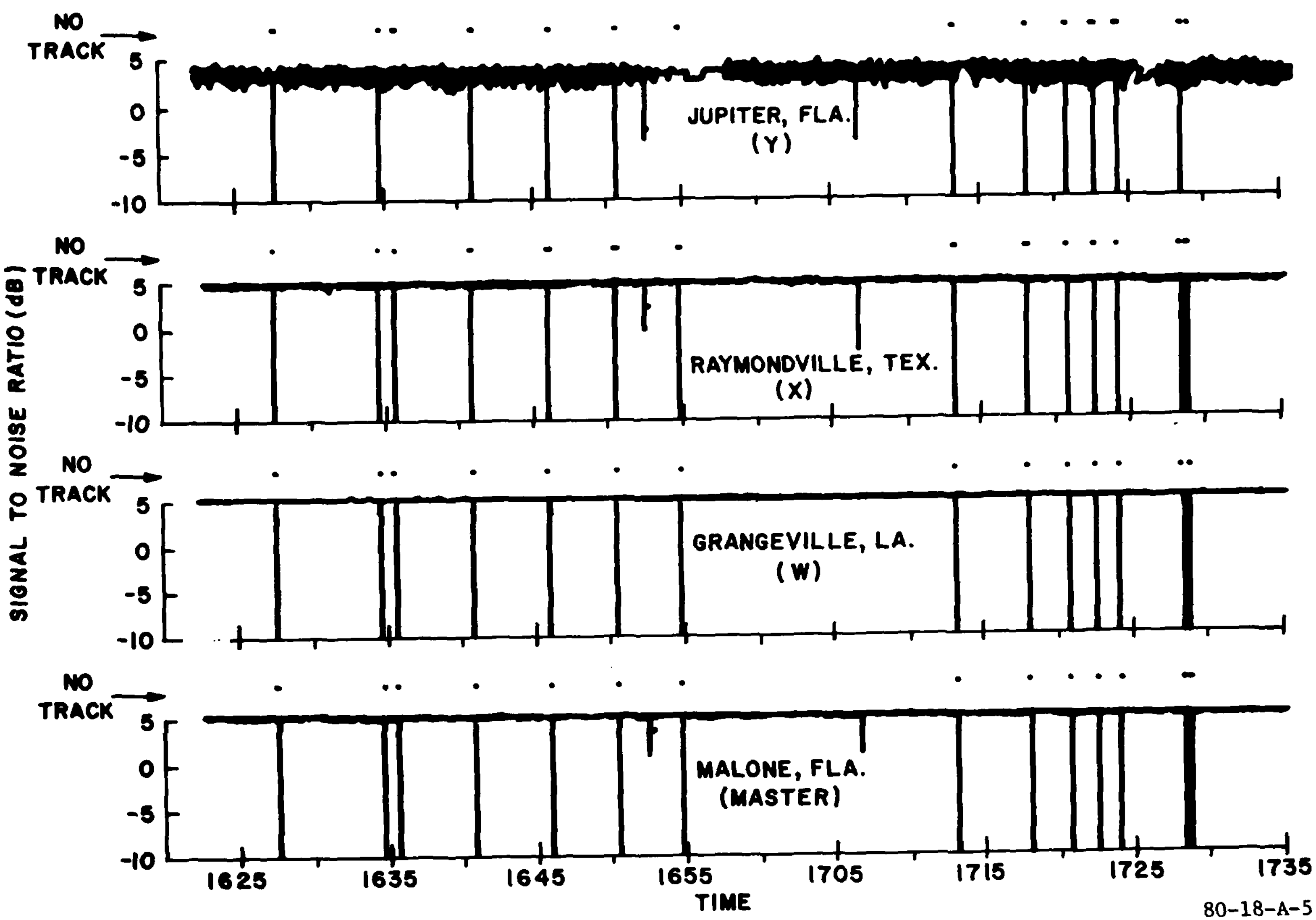

FIGURE A-5. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 1

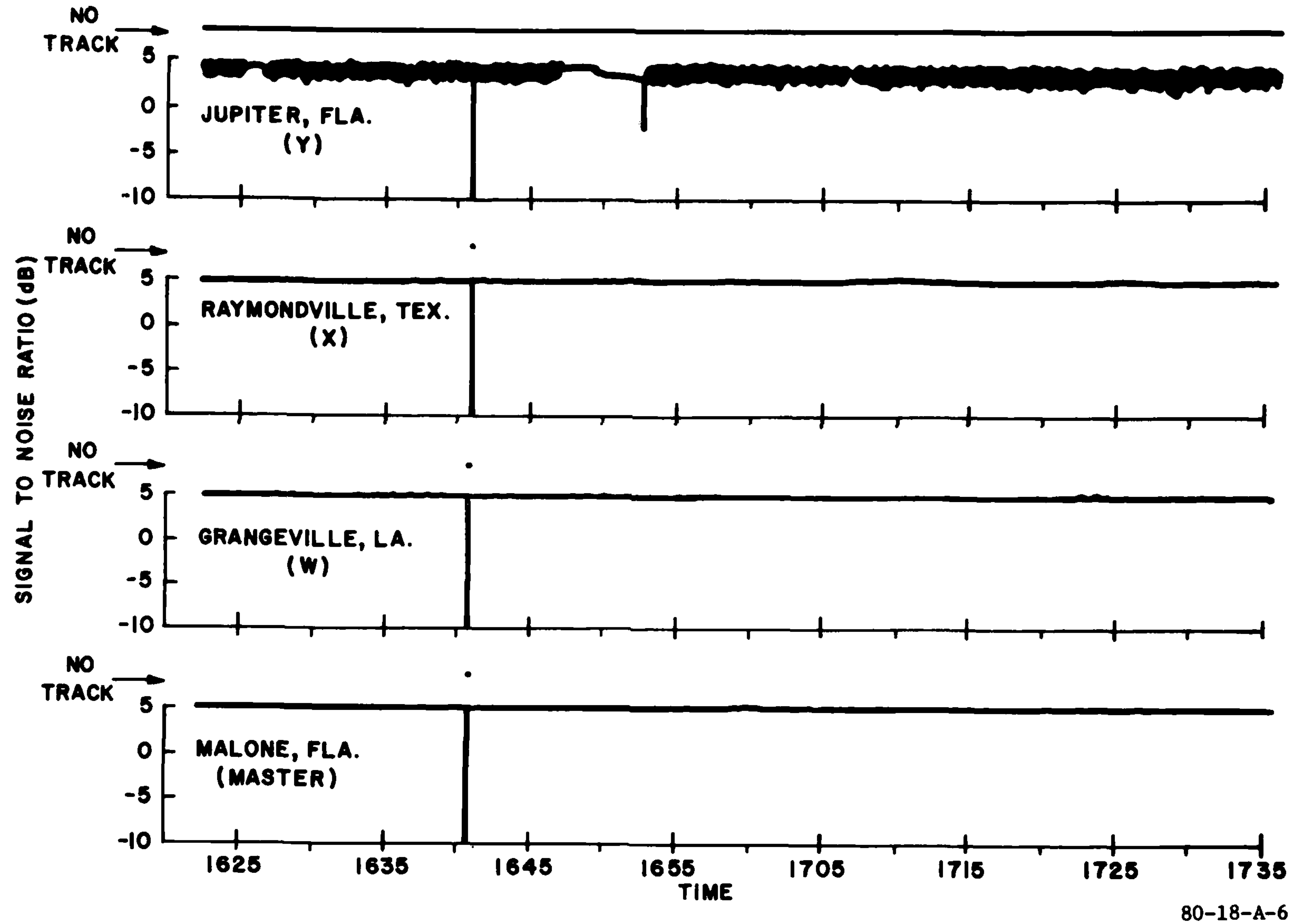

FIGURE A-6. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 2

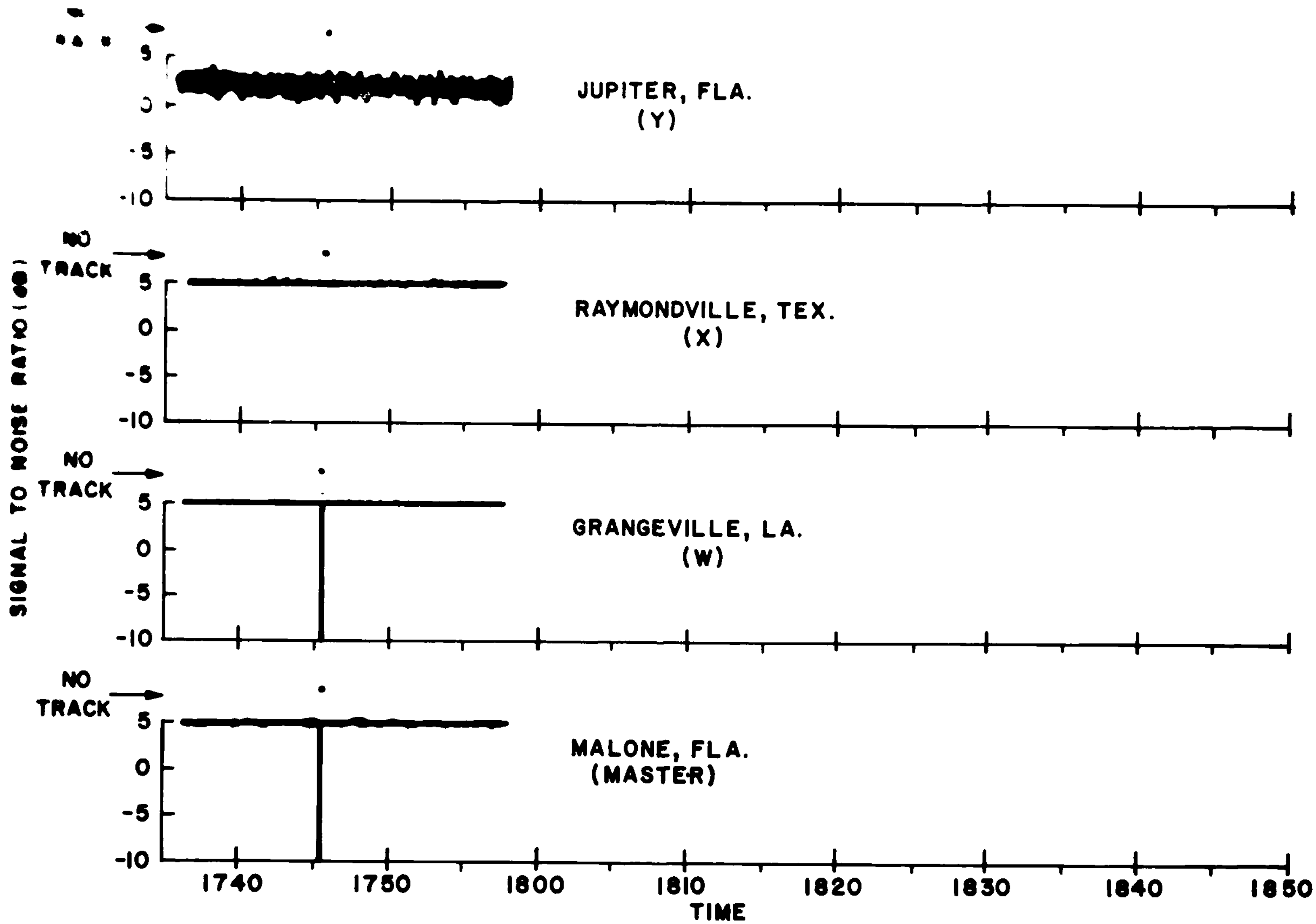

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FIGURE A-7. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 1

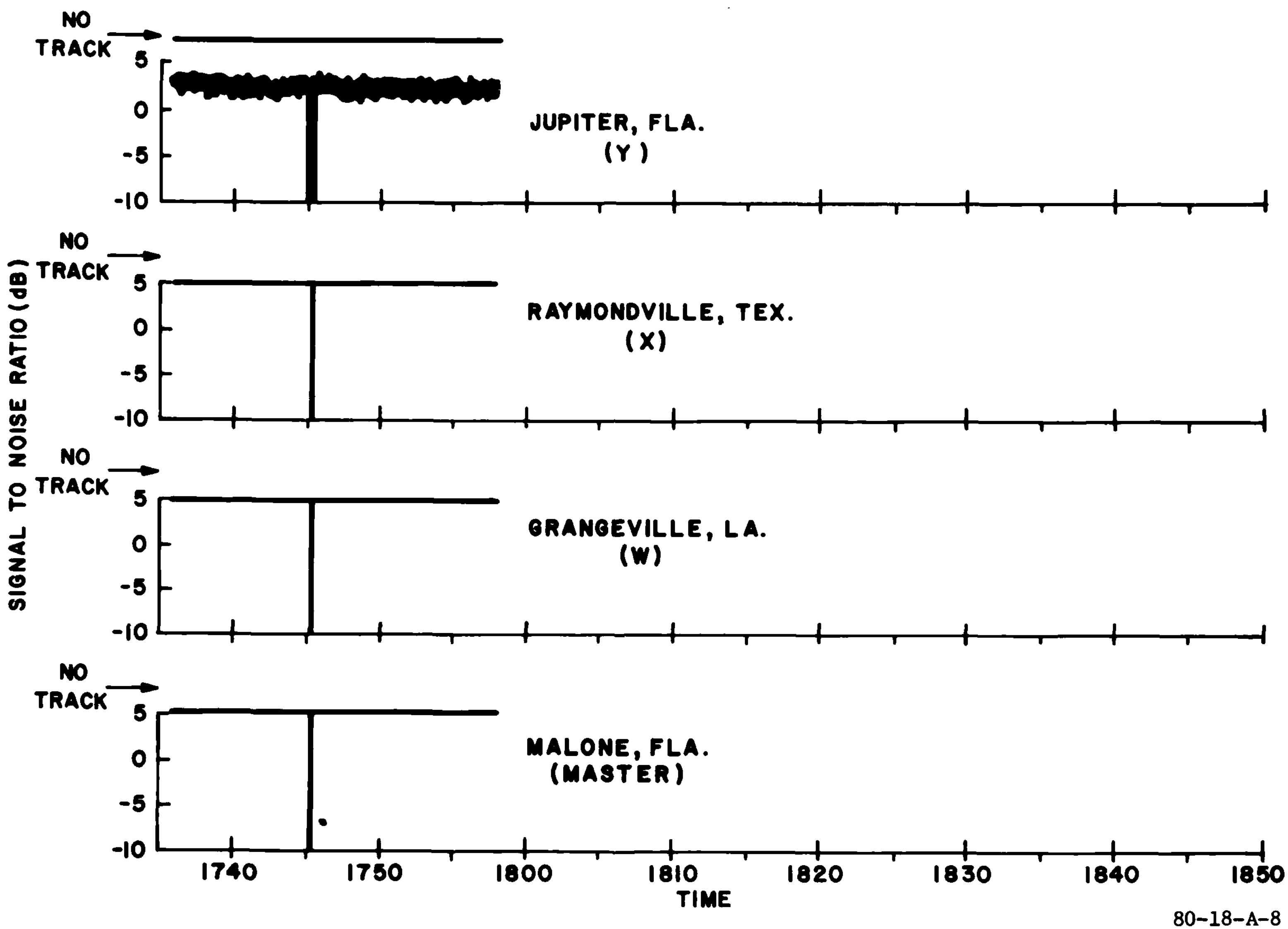

FIGURE A-8. SIGNAL-TO-NOISE RATIOS, EASTERN TEST AREA, RECEIVER 2

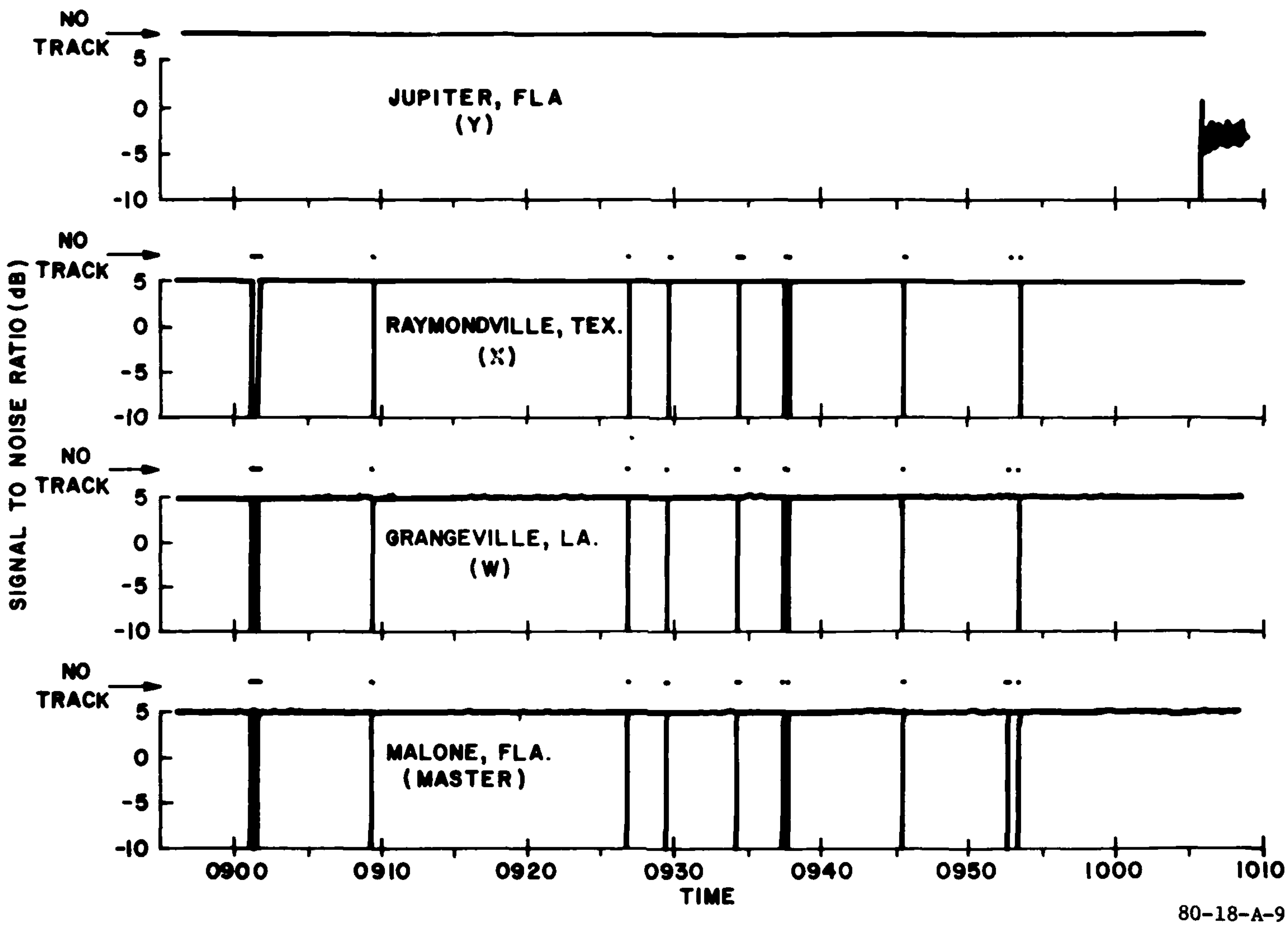

FIGURE A-9. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 1

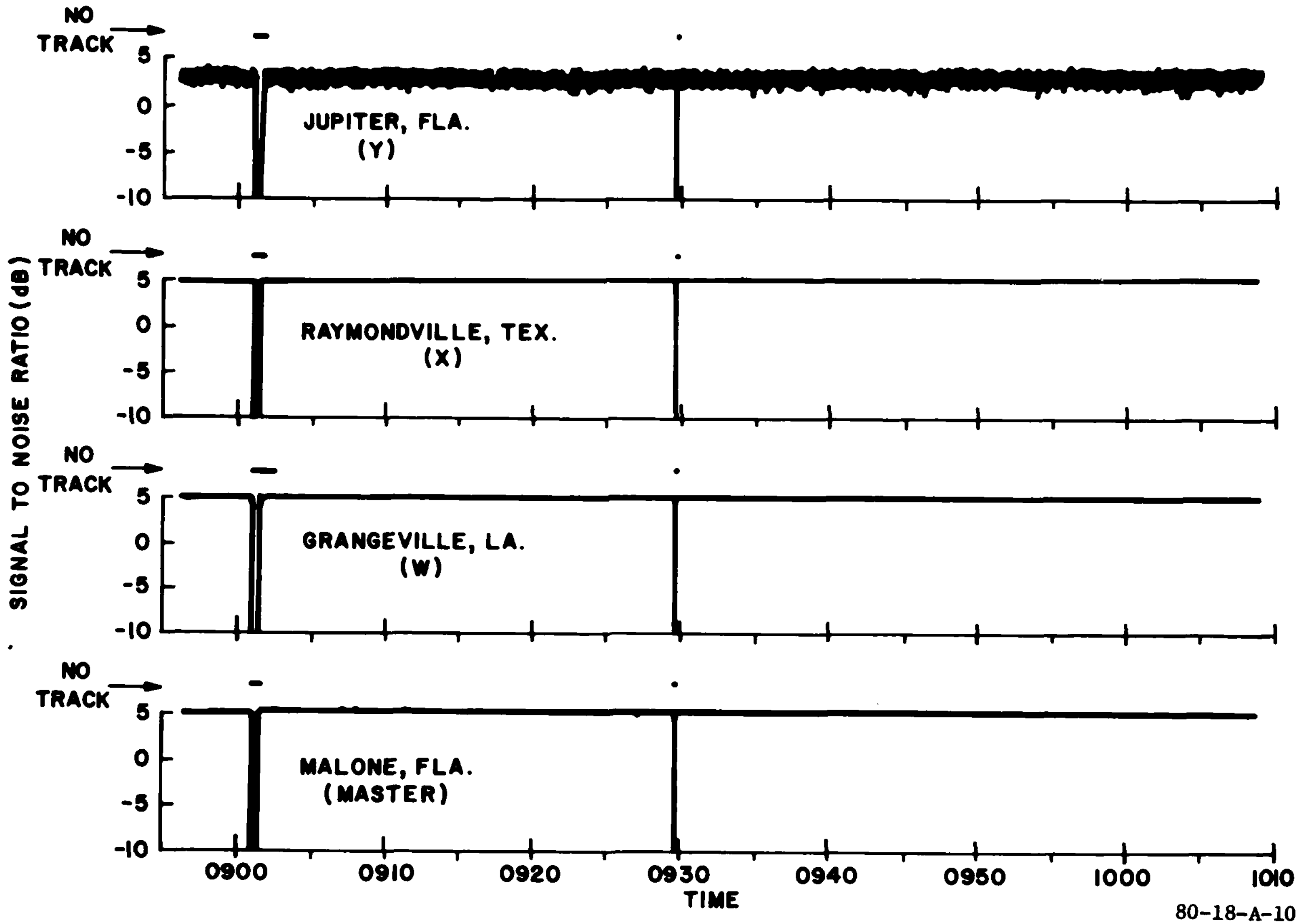

FIGURE A-10. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 2

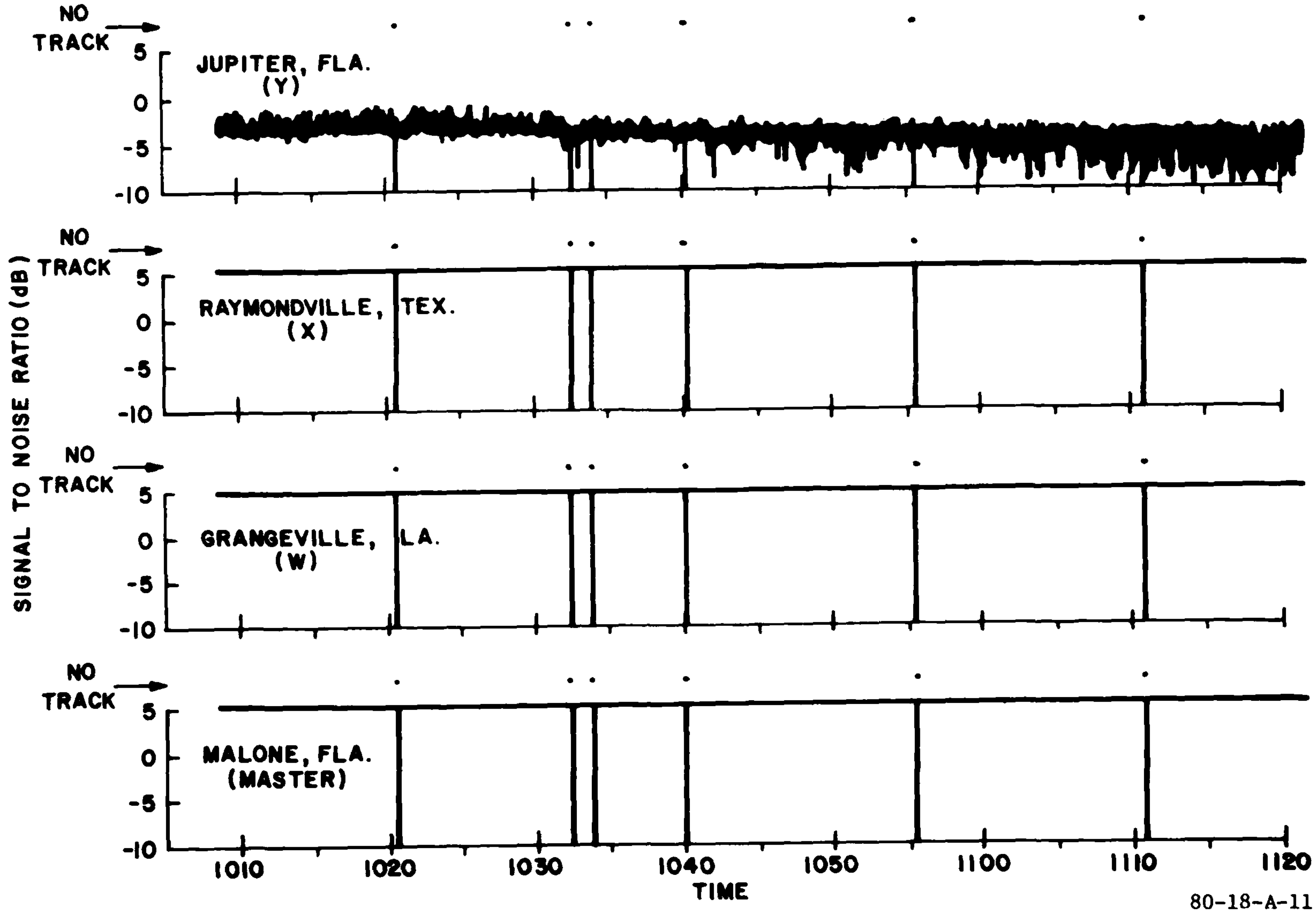

FIGURE A-11. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 1

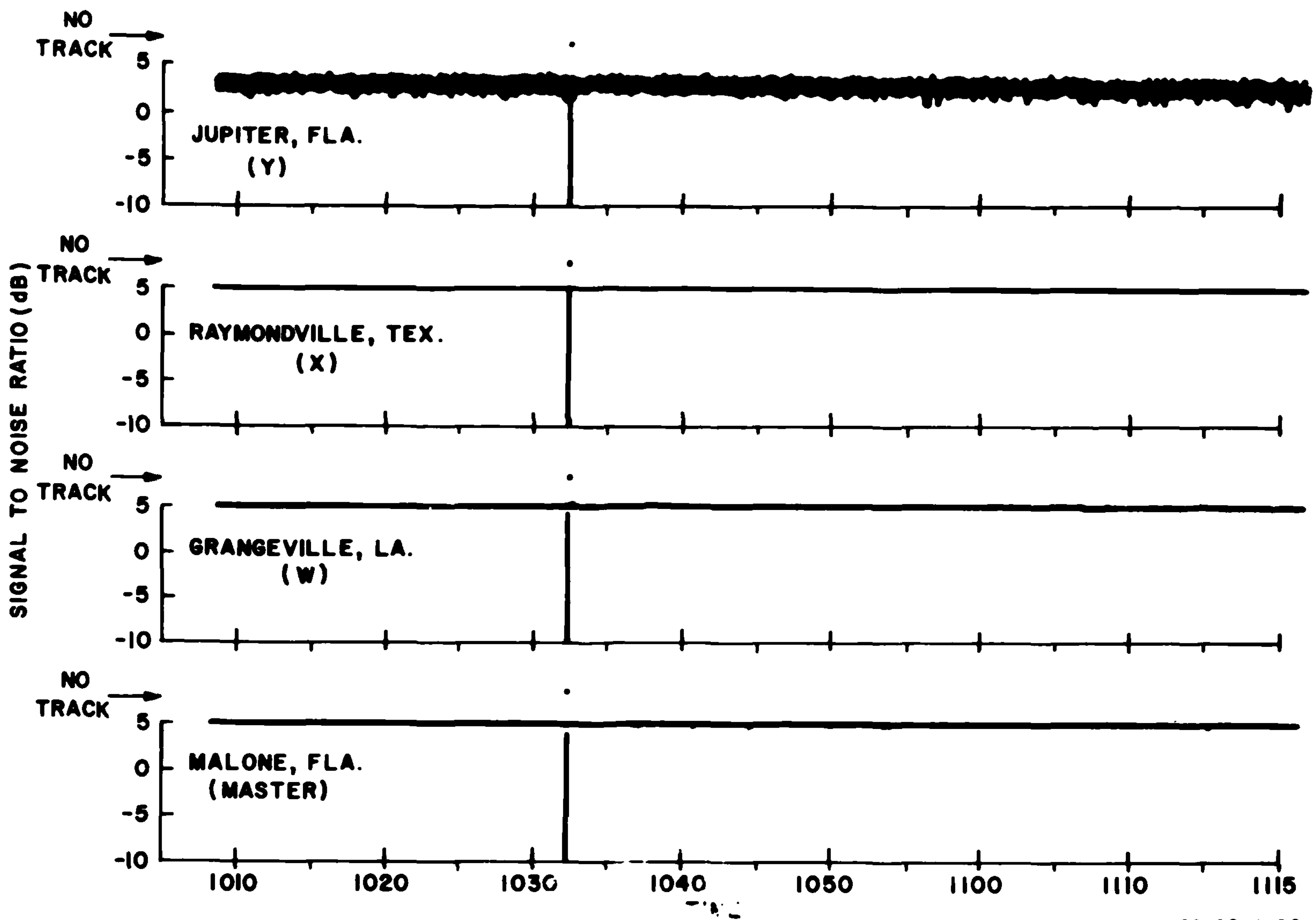

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FIGURE A-12. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 2

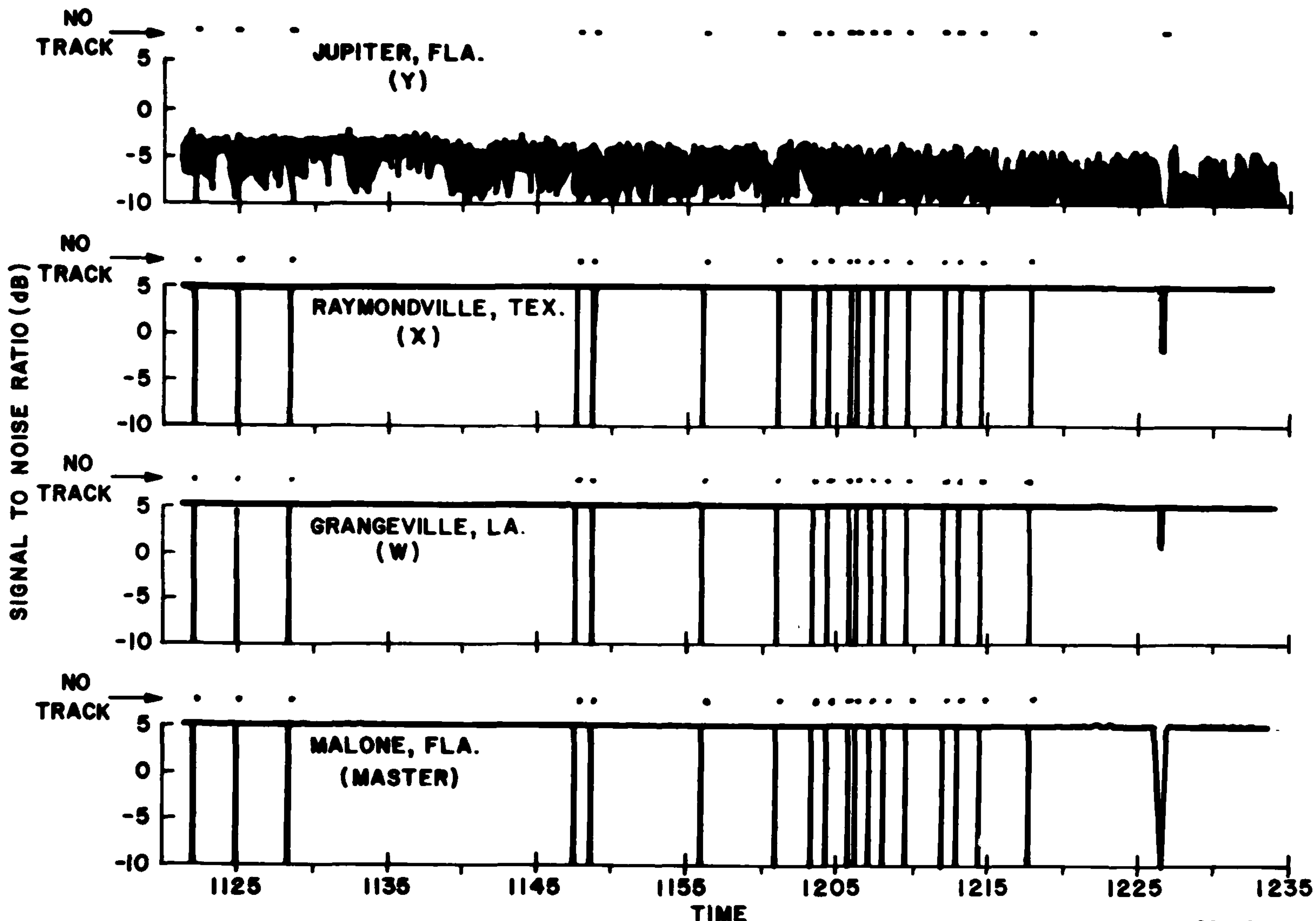

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FIGURE A-13. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 1

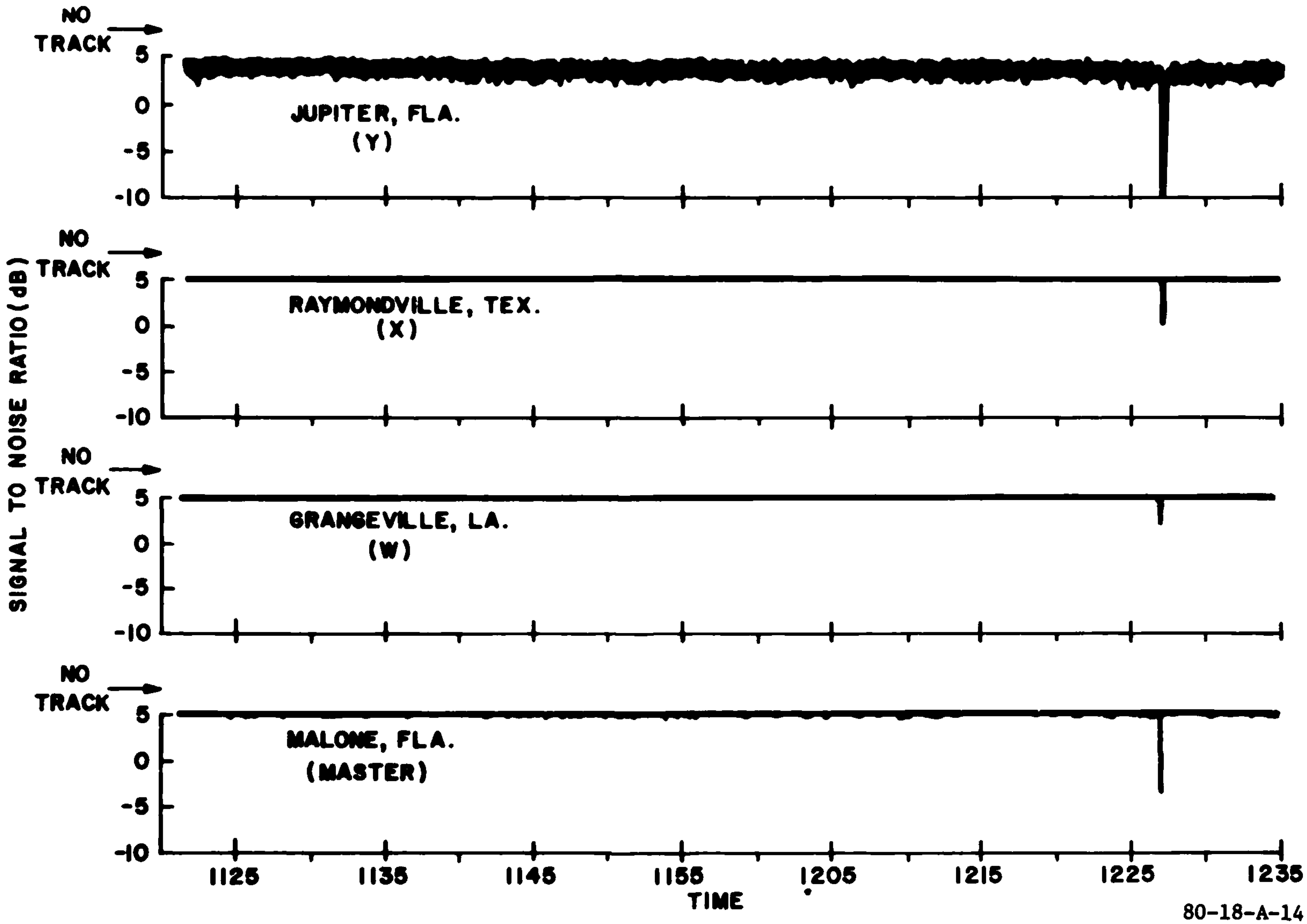

FIGURE A-14. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 2

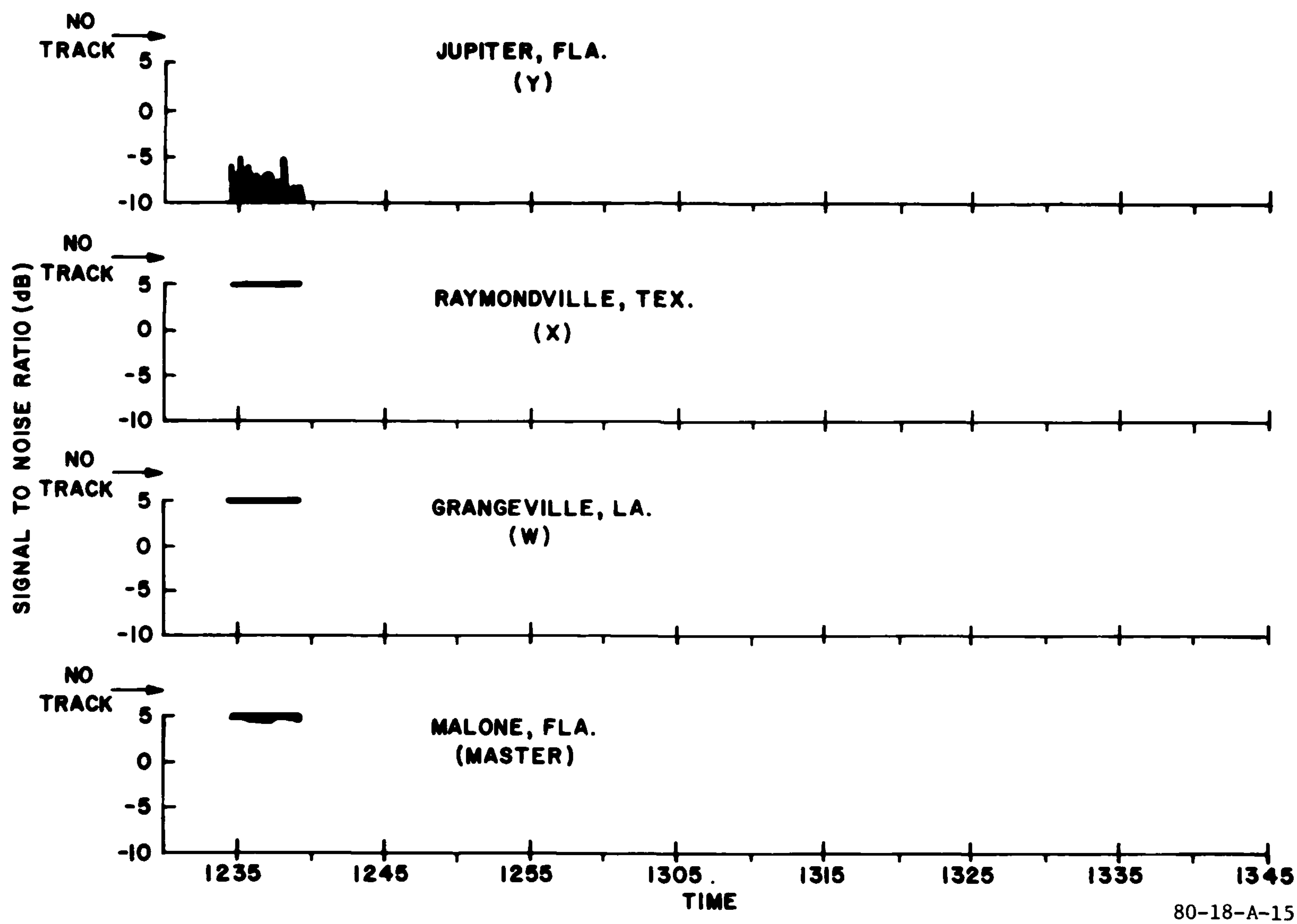

FIGURE A-15. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 1

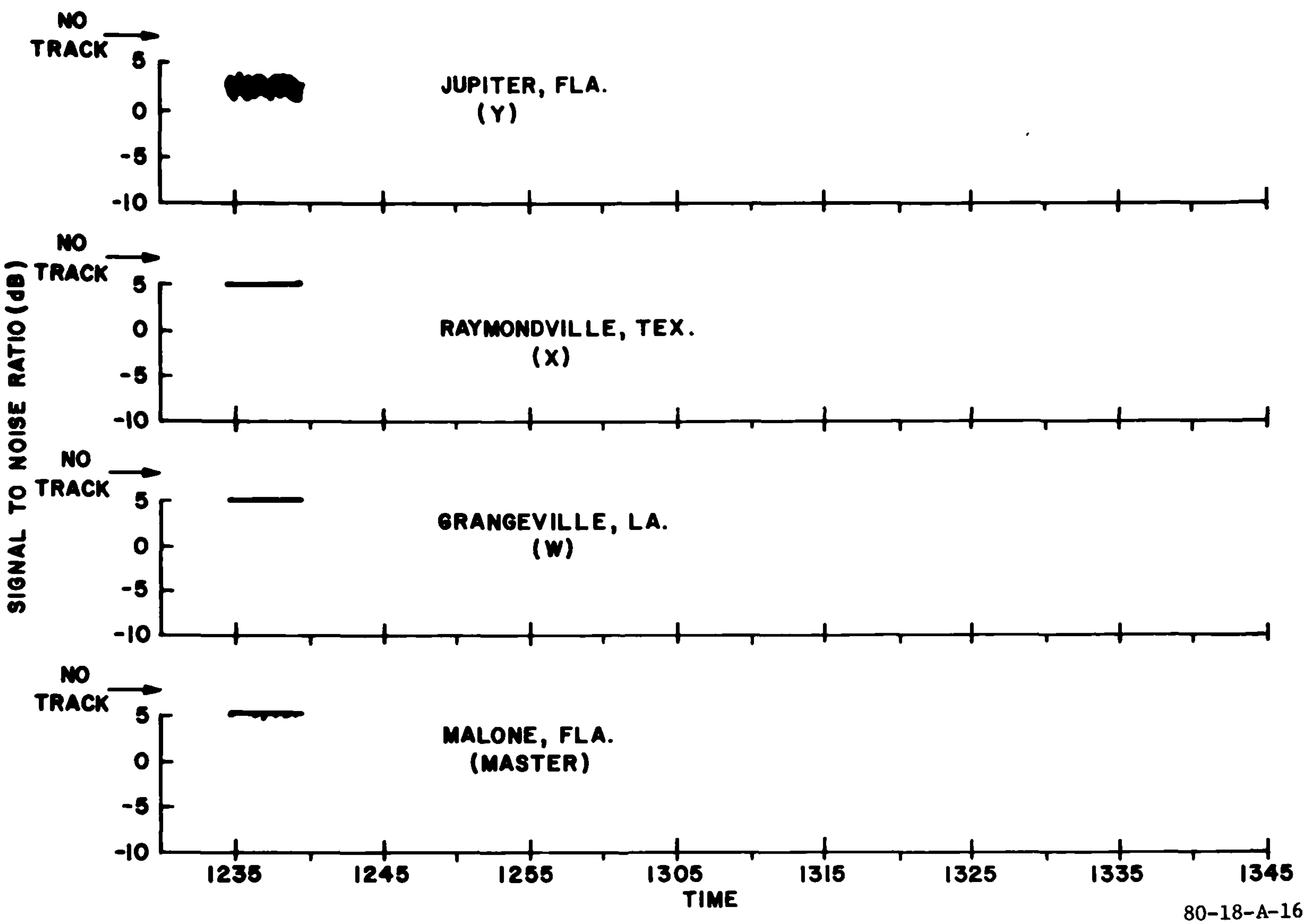

FIGURE A-16. SIGNAL-TO-NOISE RATIOS, WESTERN TEST AREA, RECEIVER 2

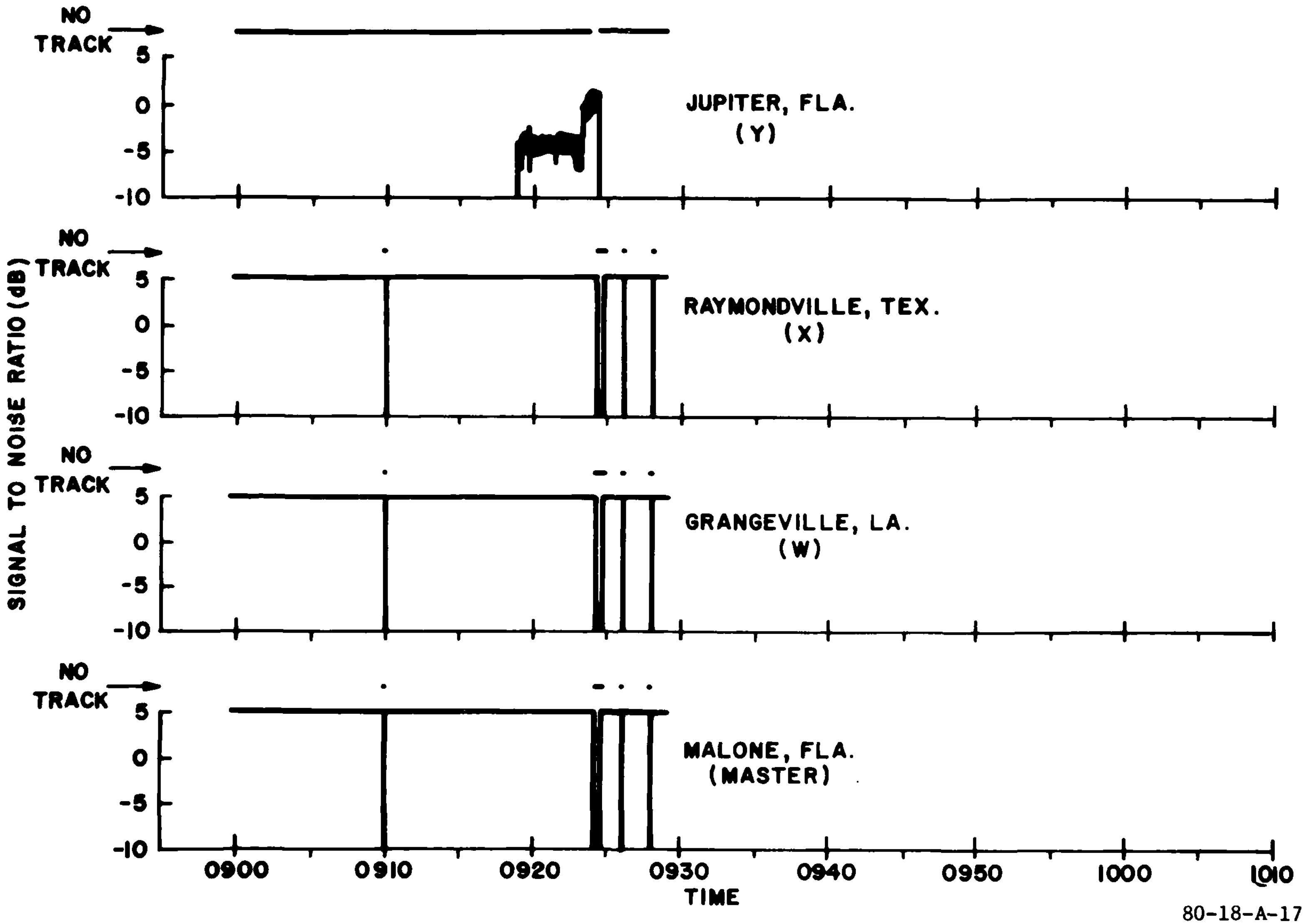

FIGURE A-17. SIGNAL-TO-NOISE RATIOS, CENTRAL TEST AREA, RECEIVER 1

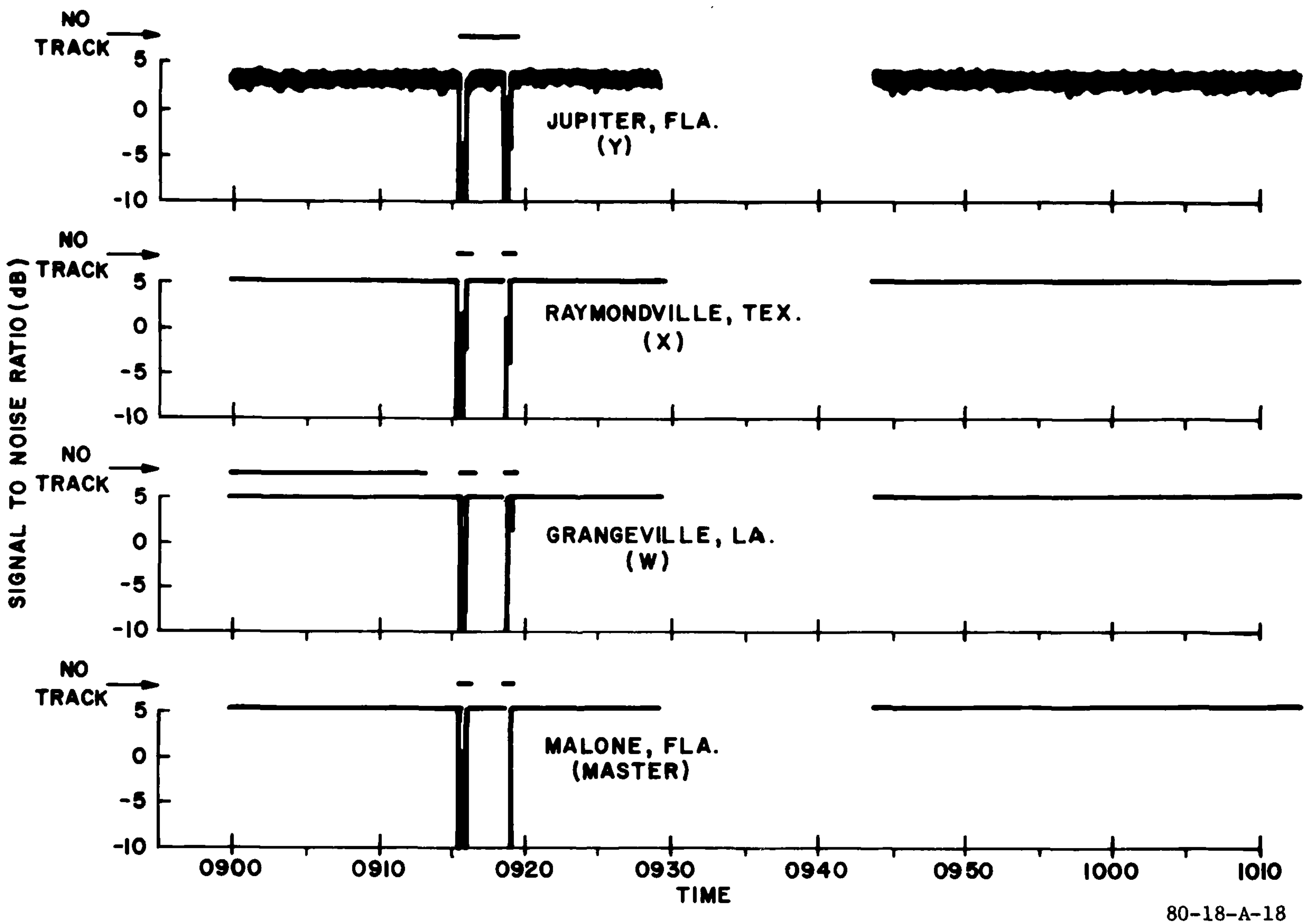

FIGURE A-18. SIGNAL-TO-NOISE RATIOS, CENTRAL TEST AREA, RECEIVER 2

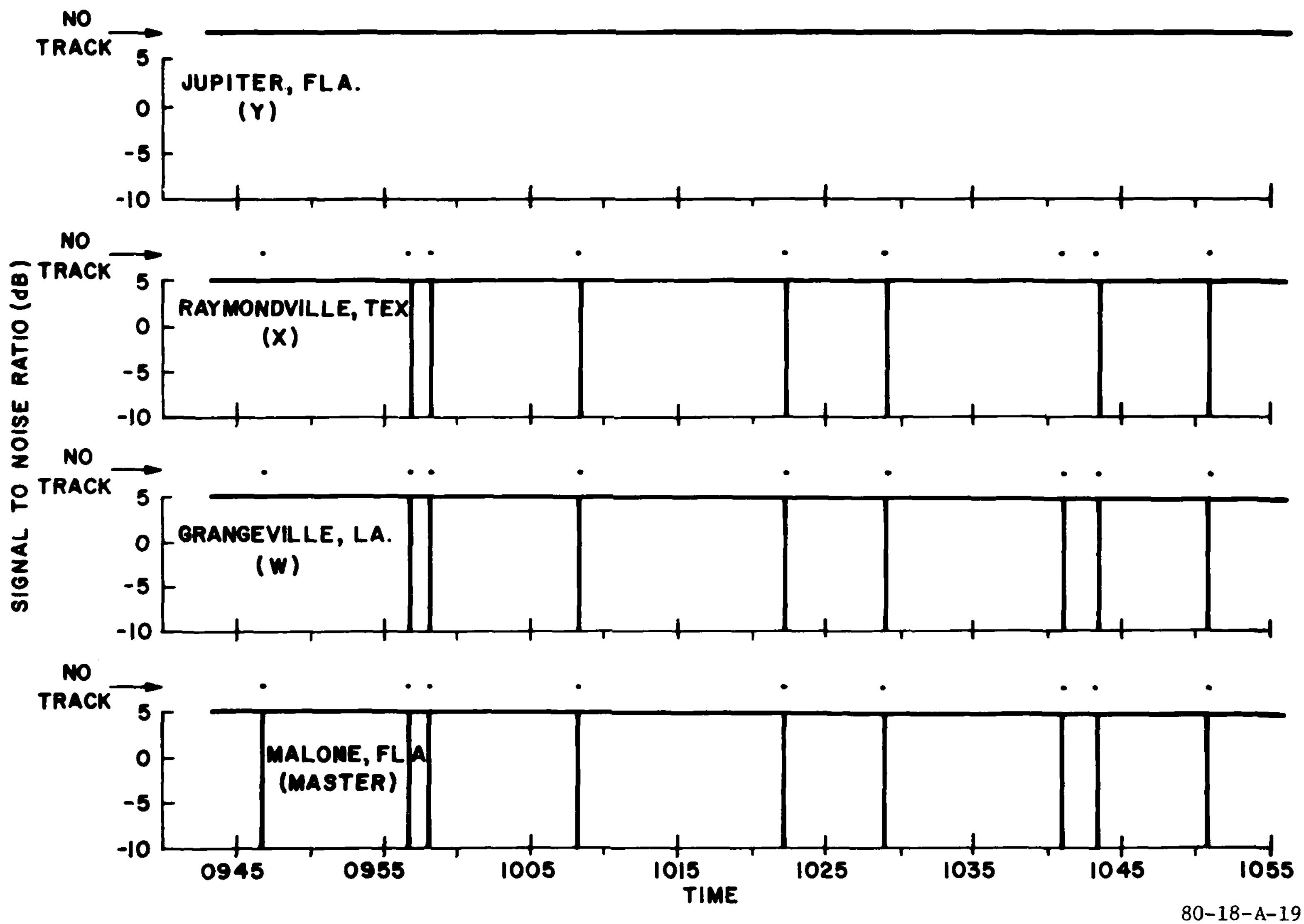

FIGURE A-19. SIGNAL-TO-NOISE RATIOS, CENTRAL TEST AREA, RECEIVER 1

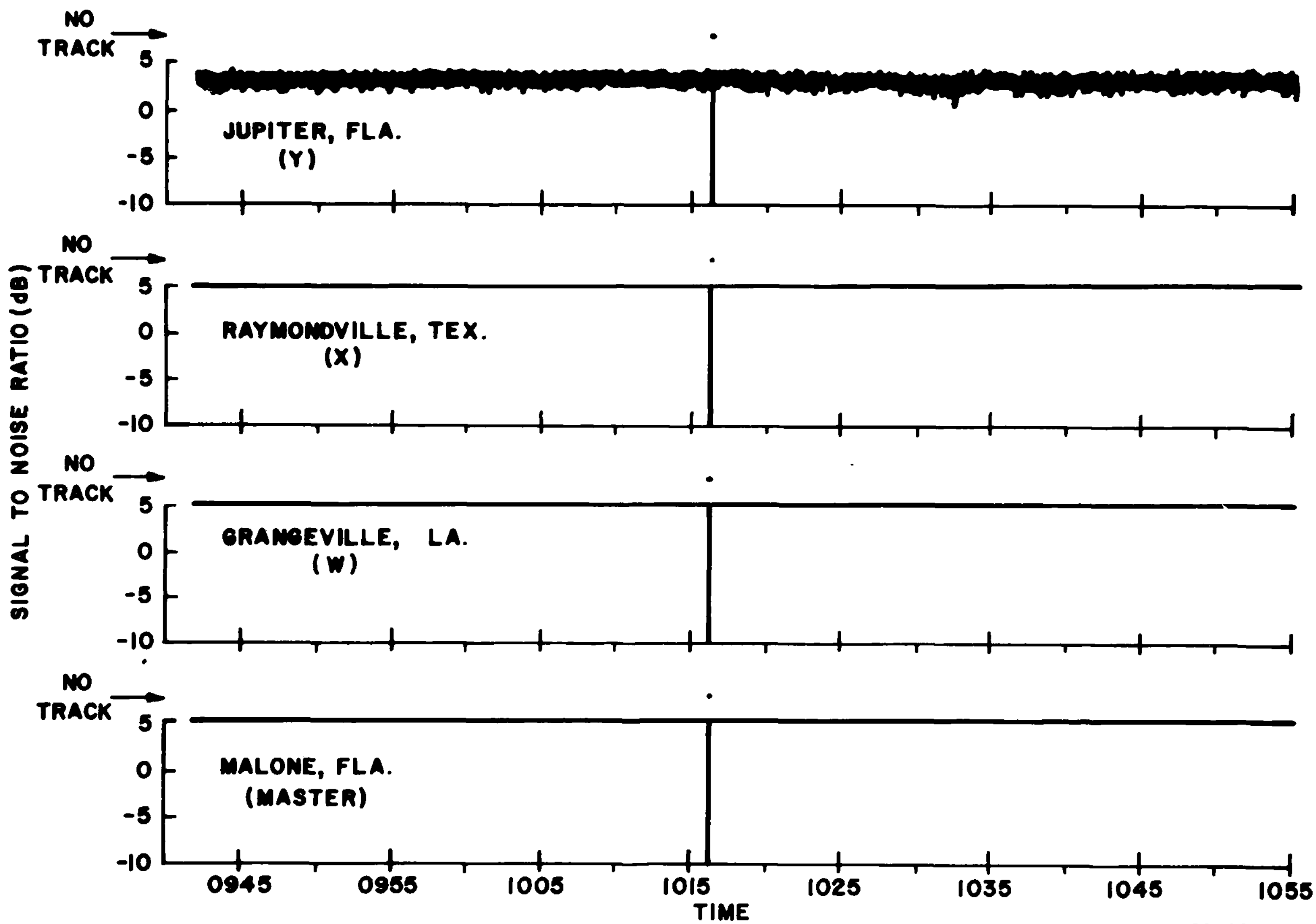

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FIGURE A-20. SIGNAL-TO-NOISE RATIOS, CENTRAL TEST AREA, RECEIVER 2

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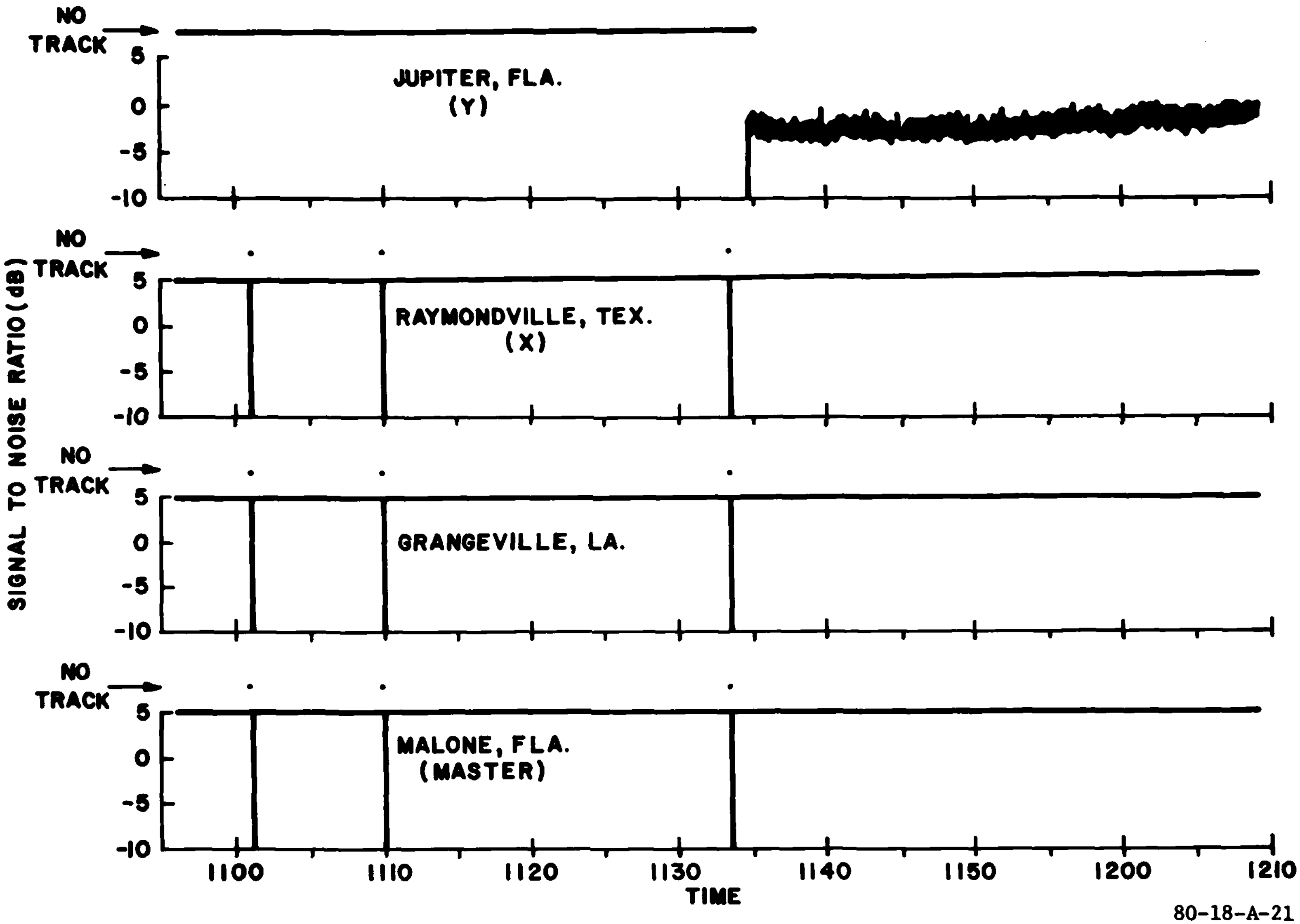

FIGURE A-21. SIGNAL-TO-NOISE RATIOS, CENTRAL TEST AREA, RECEIVER 1

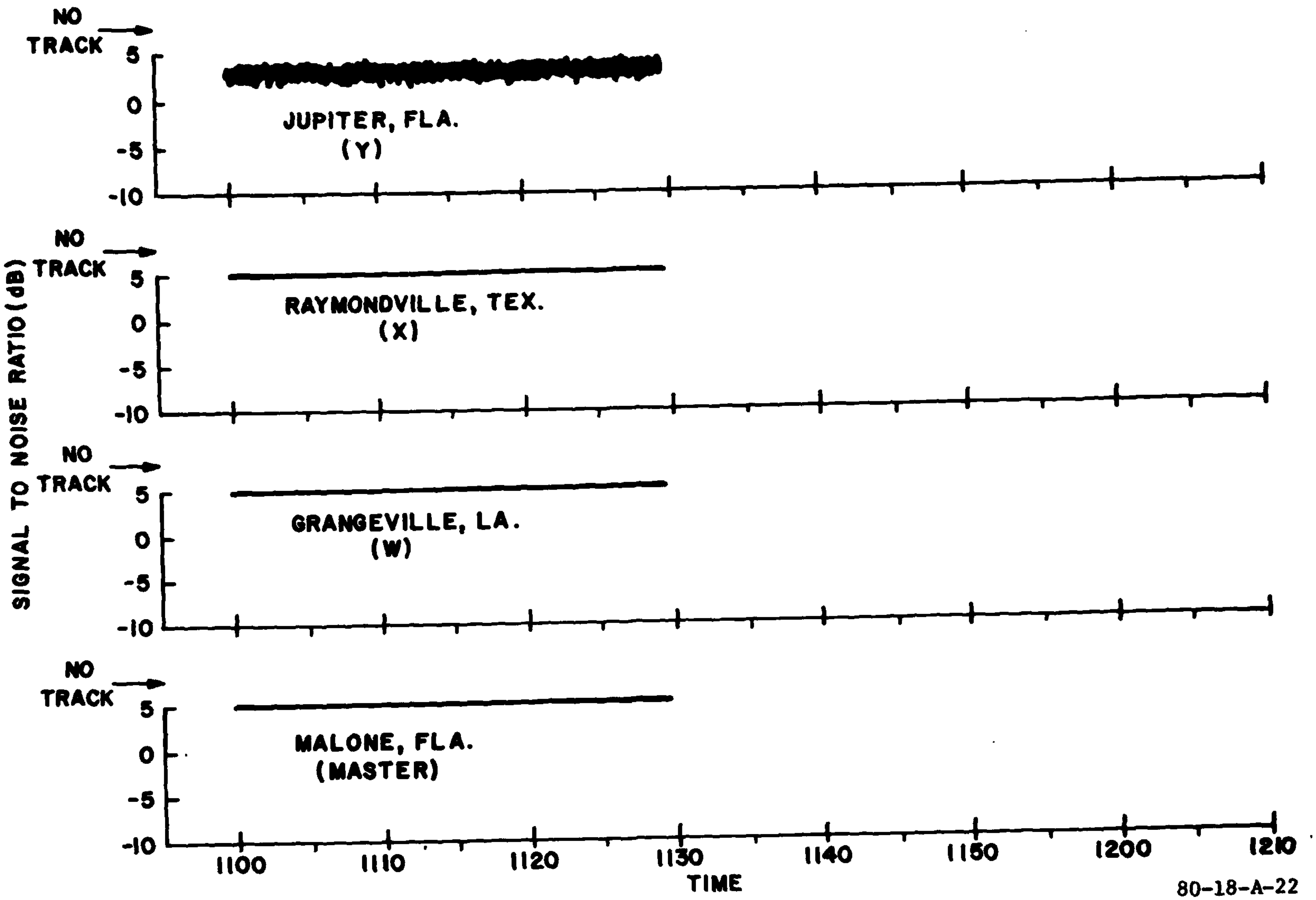

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FIGURE A-22. SIGNAL-TO-NOISE RATIOS, CENTRAL TEST AREA, RECEIVER 2

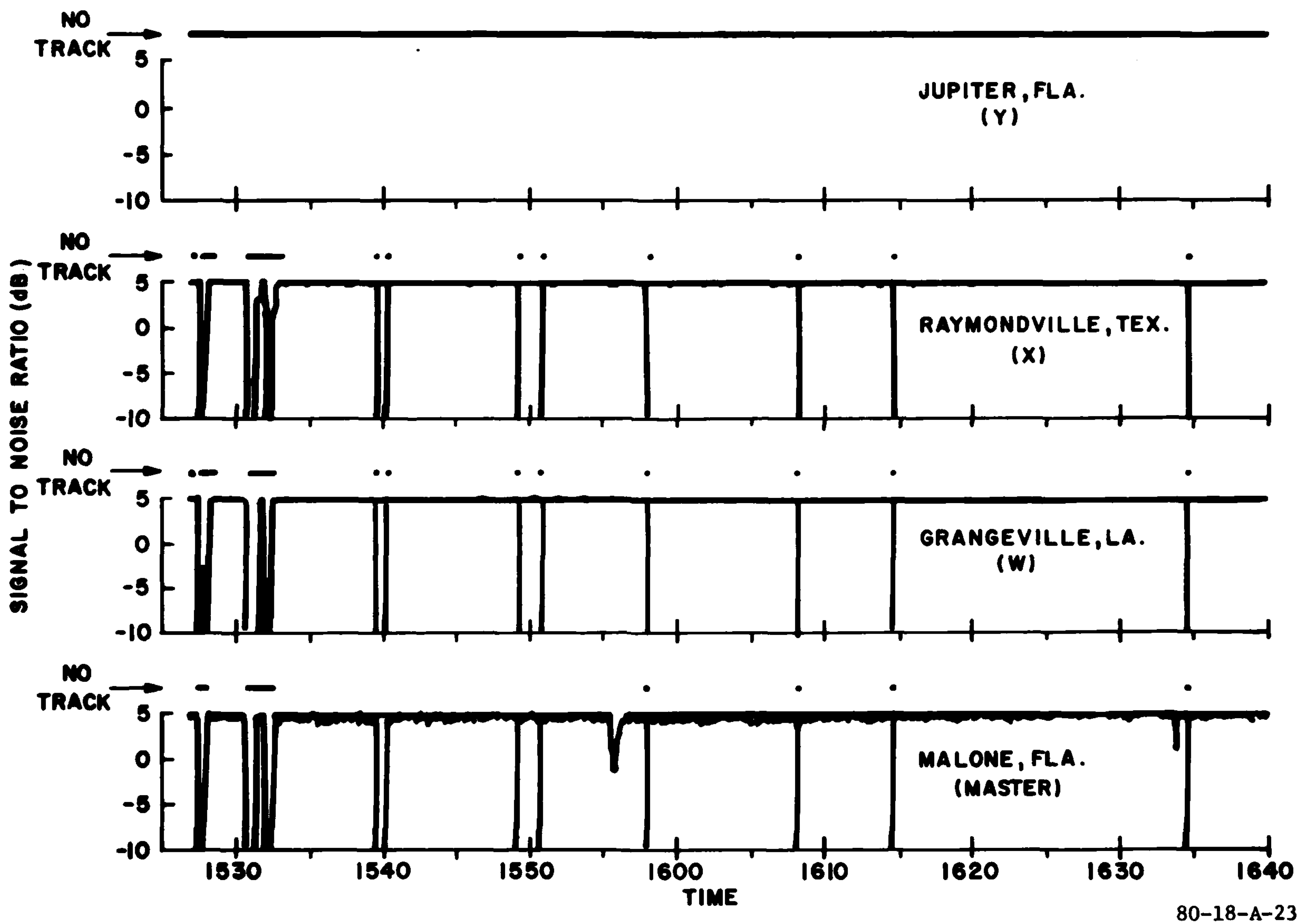

FIGURE A-23. SIGNAL-TO-NOISE RATIOS, HOUSTON TO LAFAYETTE, RECEIVER 1

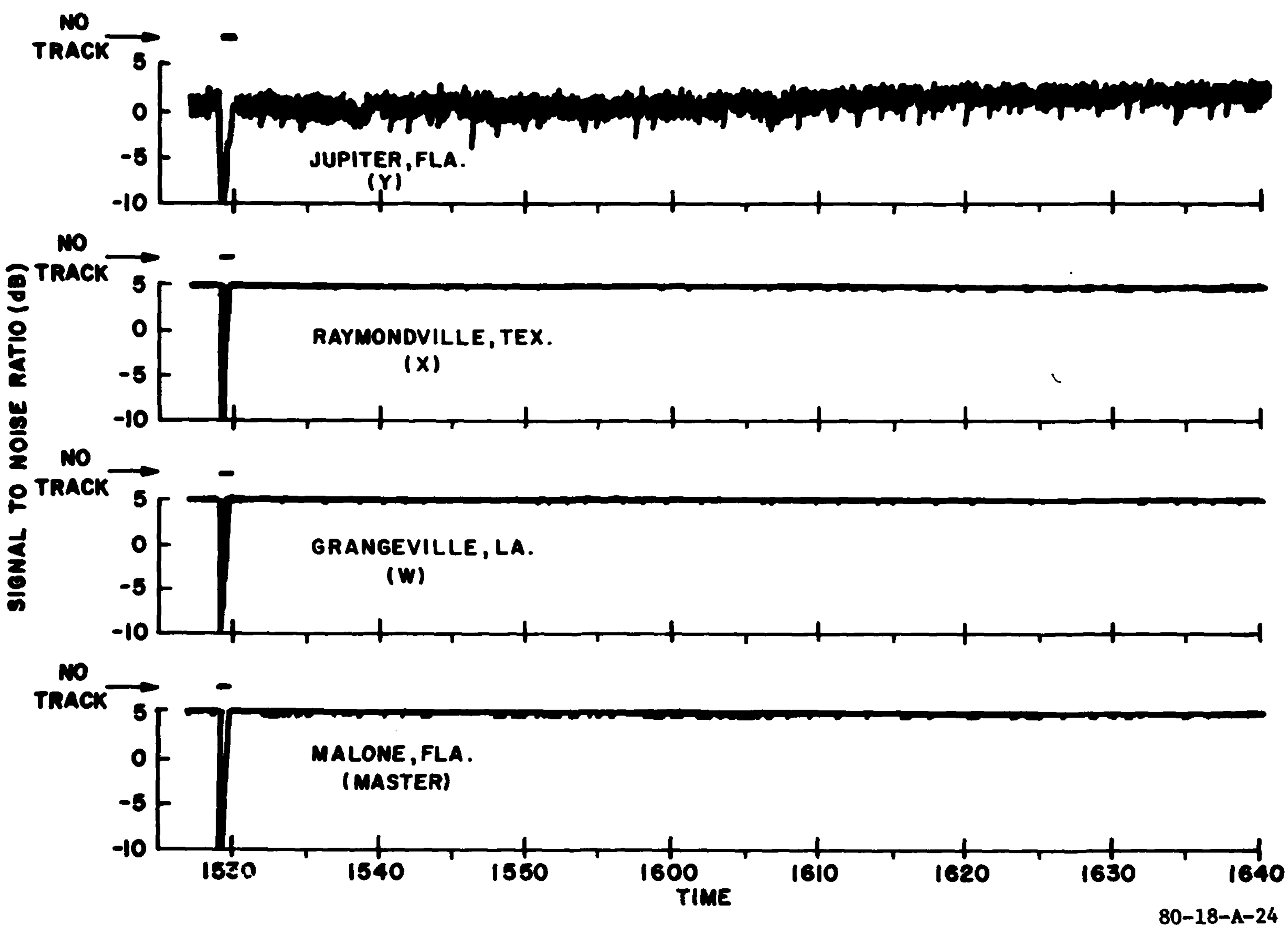

FIGURE A-24. SIGNAL-TO-NOISE RATIOS, HOUSTON TO LAFAYETTE, RECEIVER 2

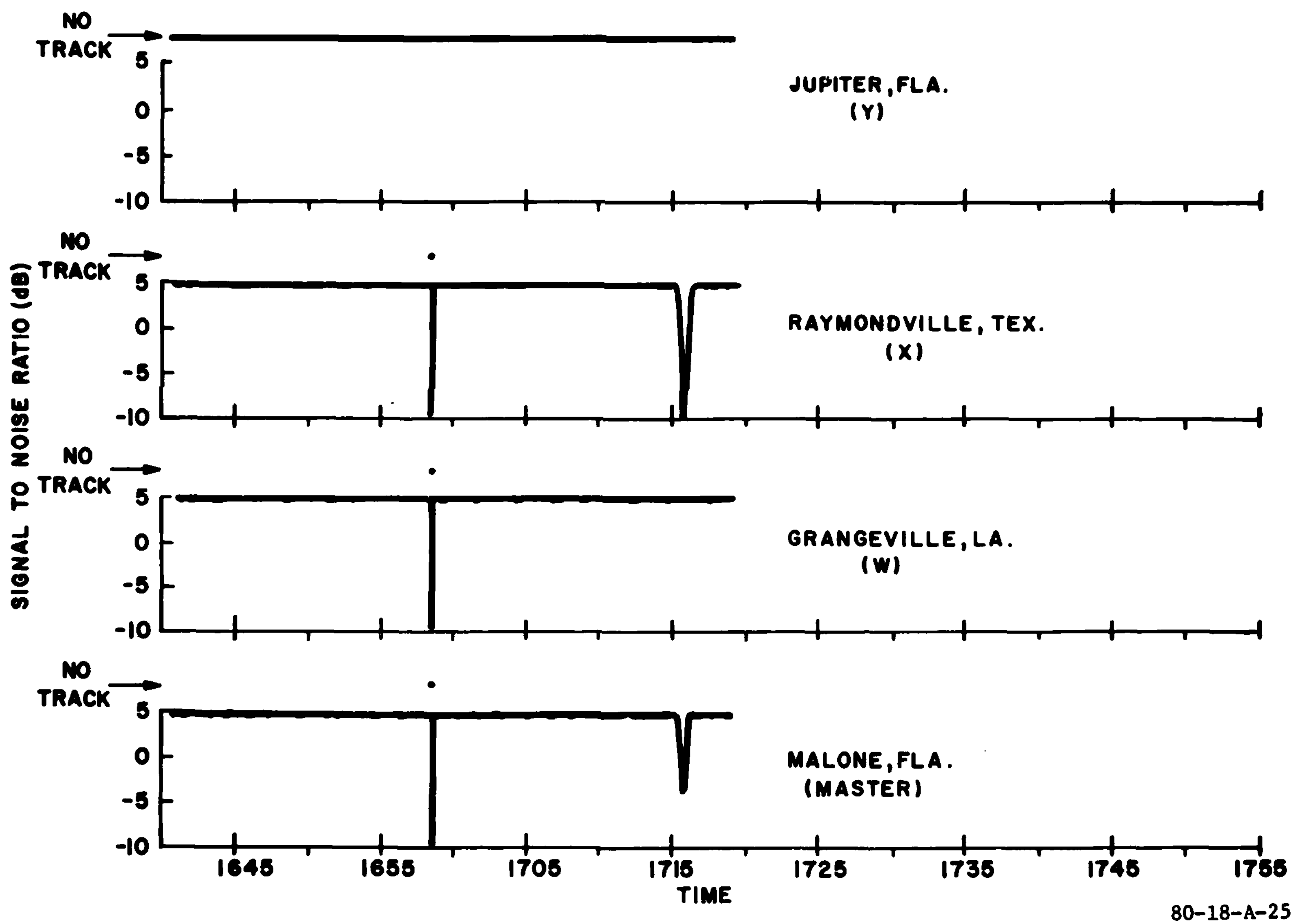

FIGURE A-25. SIGNAL-TO-NOISE RATIOS, HOUSTON TO LAFAYETTE, RECEIVER 1

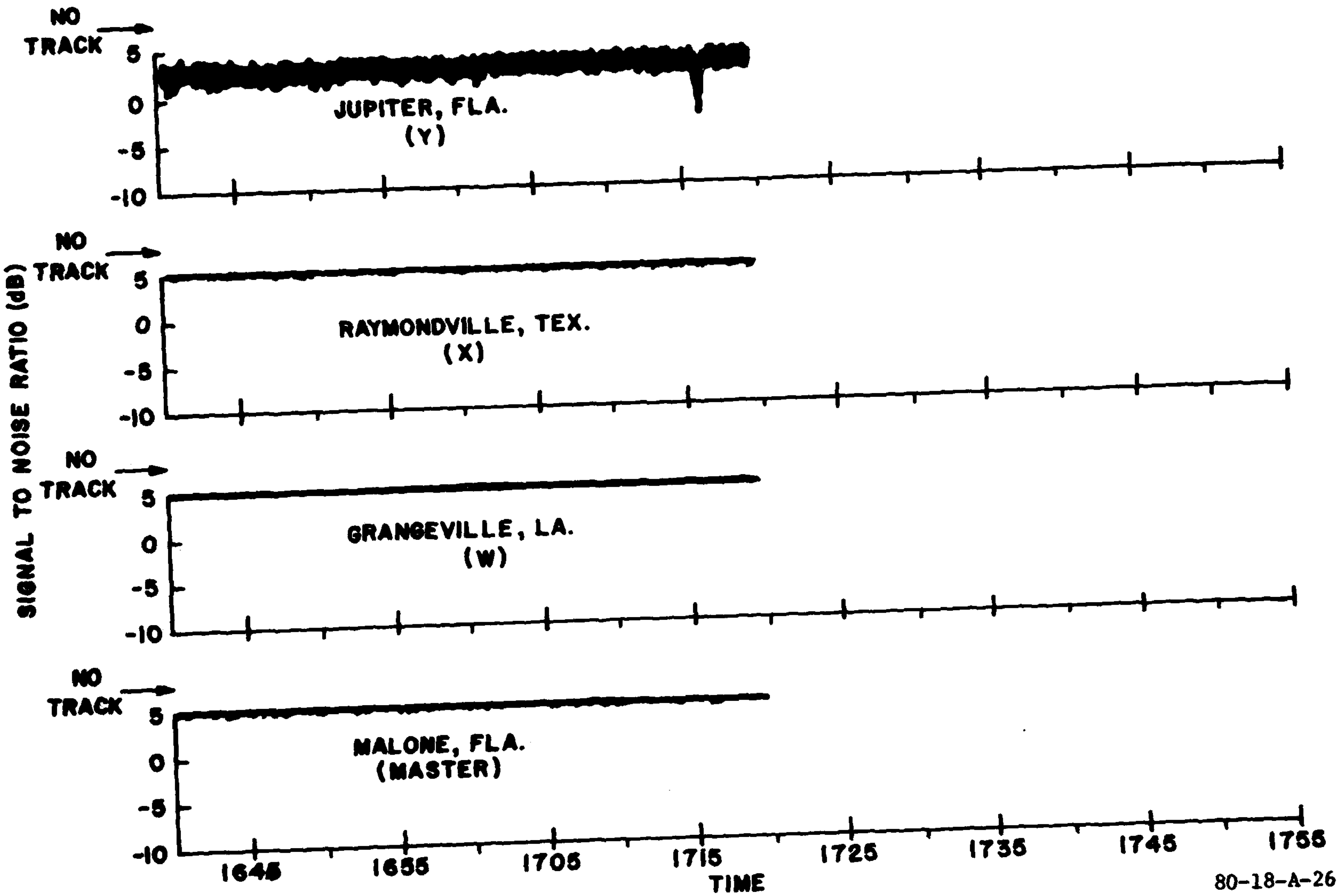

FIGURE A-26. SIGNAL-TO-NOISE RATIOS, HOUSTON TO LAFAYETTE, RECEIVER 2

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